

Recent developments in neutrino-nucleus scattering theory

Marco Martini



Neutrino - nucleus cross sections and neutrino oscillations

- Neutrino oscillation experiments require the determination of the neutrino energy which enters the expression of the oscillation probability

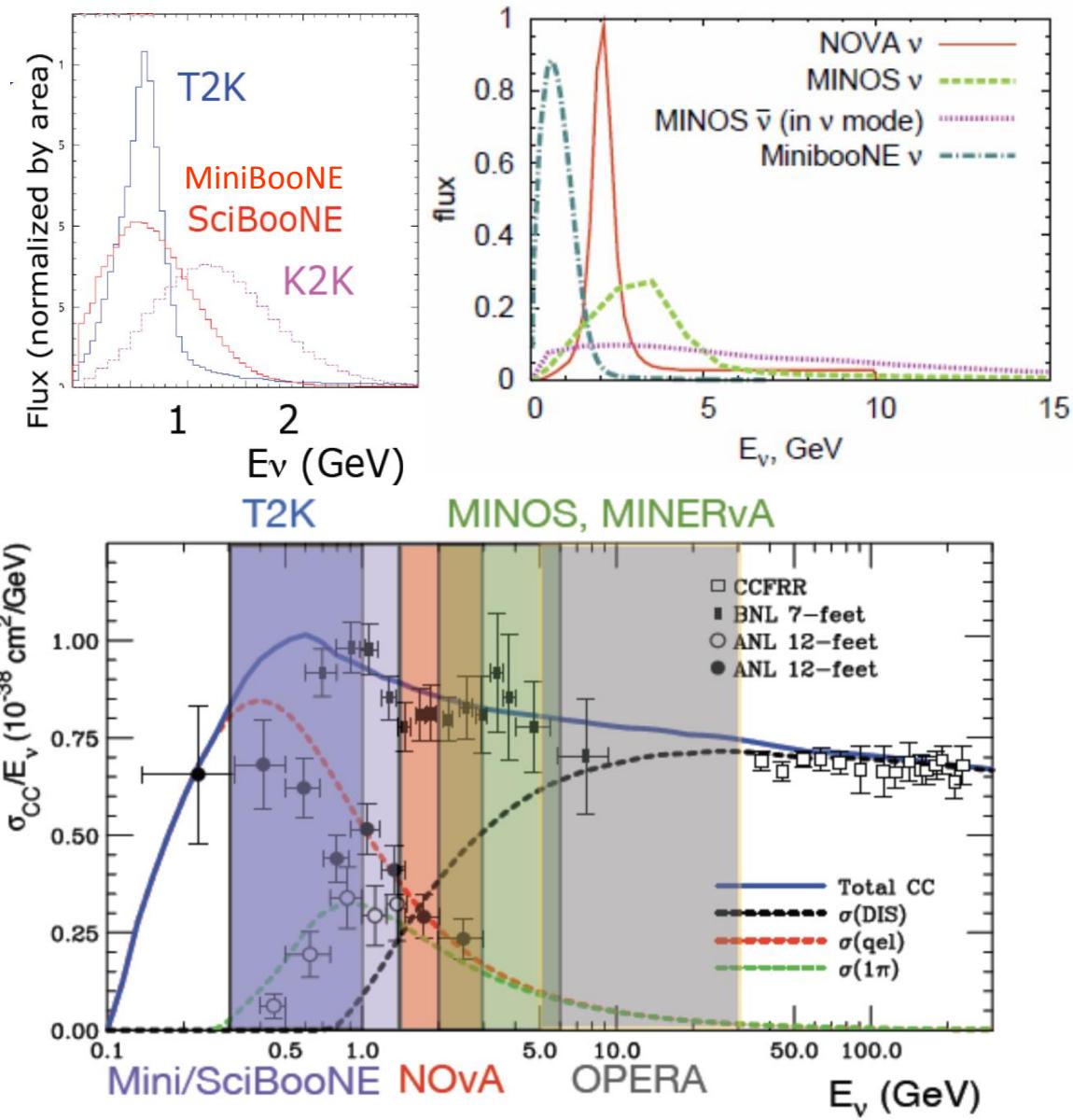
e.g.

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E_\nu} \right)$$

- Modern neutrino oscillation experiments use nuclear targets (C, O, Ar, Fe...)
- Nuclear effects play a crucial role

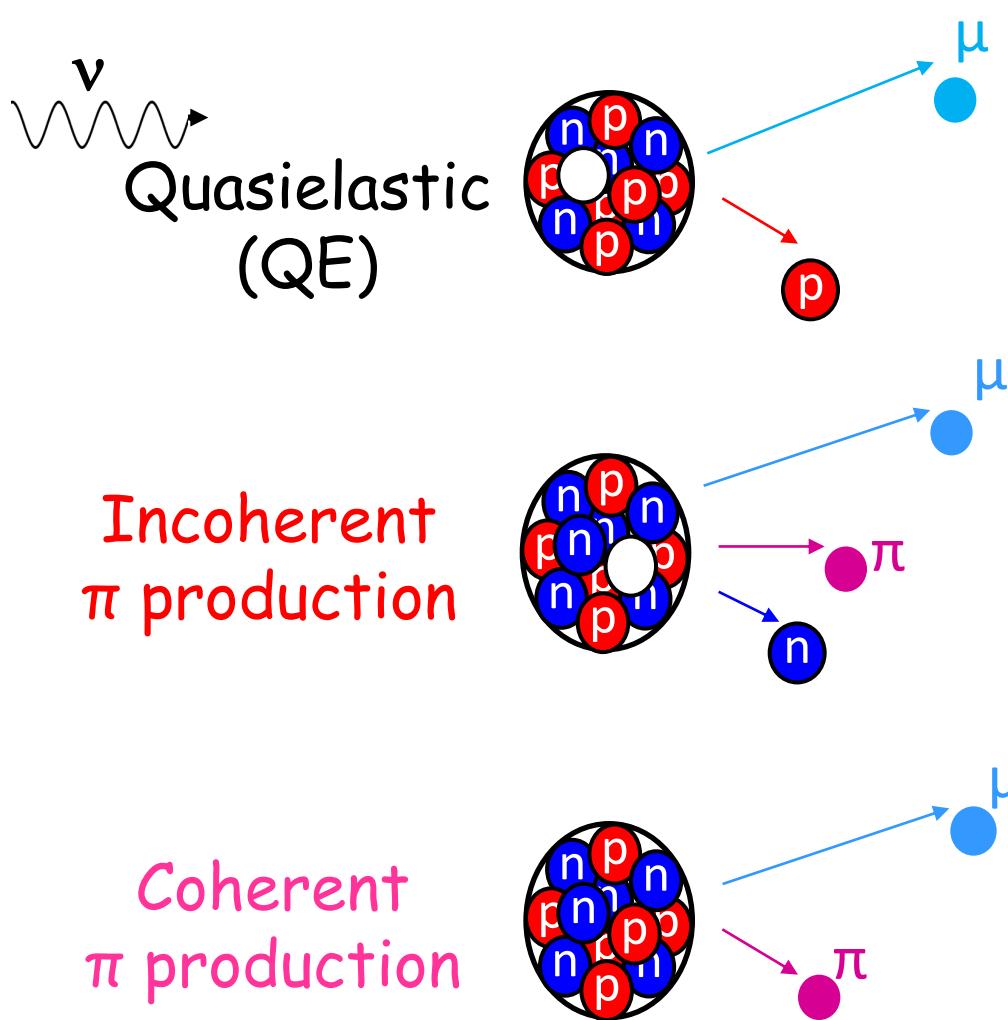
Some crucial points

- Neutrino beams are not monochromatic (at difference with respect to electron beams). They span a wide range of energies
- The neutrino energy is reconstructed from the final states of the reaction (typically from CC Quasielastic events)
- Different reaction mechanisms contribute to the cross section in the modern experiments

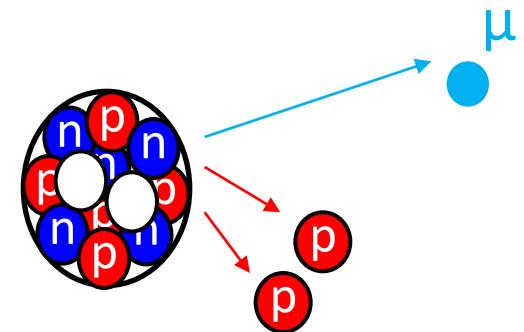


Neutrino - nucleus interaction @ $E_\nu \sim 0$ (1 GeV)

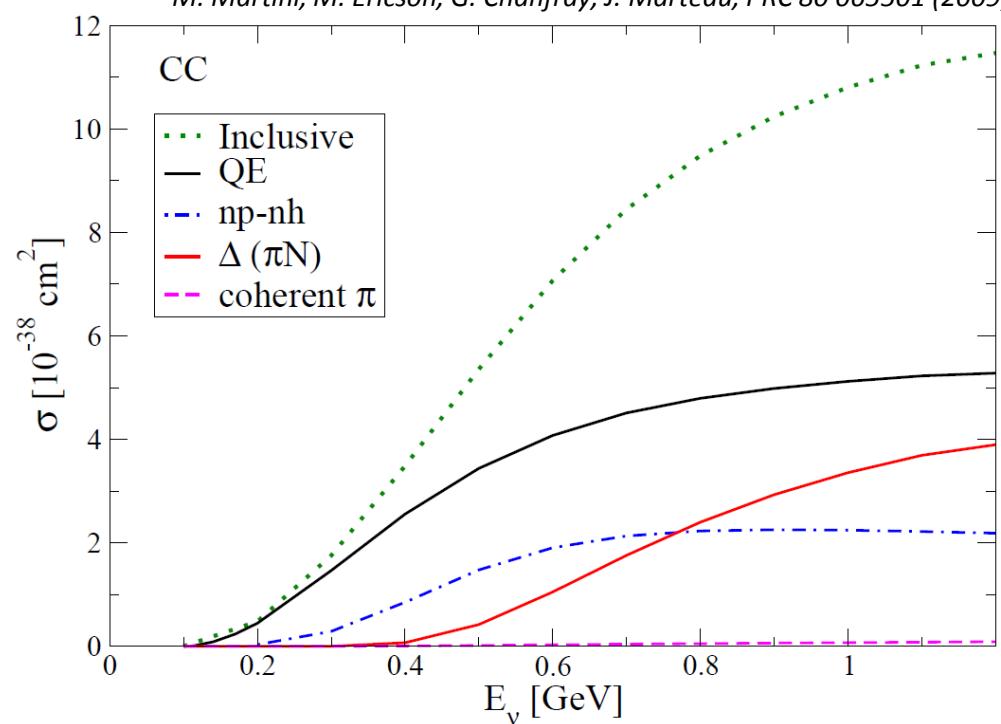
[MiniBooNE, T2K energies]



Two Nucleons
knock-out
(2p-2h)



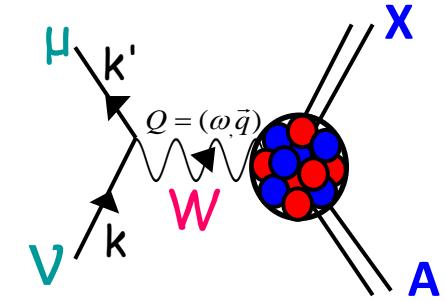
M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)



Coherent
 π production

Different processes are entangled

Neutrino-nucleus cross section



$$d\sigma \propto L_{\mu\nu} W^{\mu\nu}$$

$$L_{\mu\nu} = k_\mu k'_\nu + k'_\mu k_\nu - g_{\mu\nu} k \cdot k' \pm i\varepsilon_{\mu\nu\kappa\lambda} k^\kappa k'^\lambda \quad W^{\mu\nu} = \sum_f \langle \Psi_f | J^\mu(Q) | \Psi_i \rangle^* \langle \Psi_f | J^\nu(Q) | \Psi_i \rangle \delta(E_i + \omega - E_f)$$

Leptonic tensor

Hadronic tensor

The cross section in terms of the response functions:

$$\frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = \sigma_0 [L_{00} R_{00} + L_{0z} R_{0z} + L_{zz} R_{zz} + L_{xx} R_{xx} \pm L_{xy} R_{xy}]$$

Longitudinal

Transverse

Transverse
V-A interference

A simplified expression (useful for illustration):

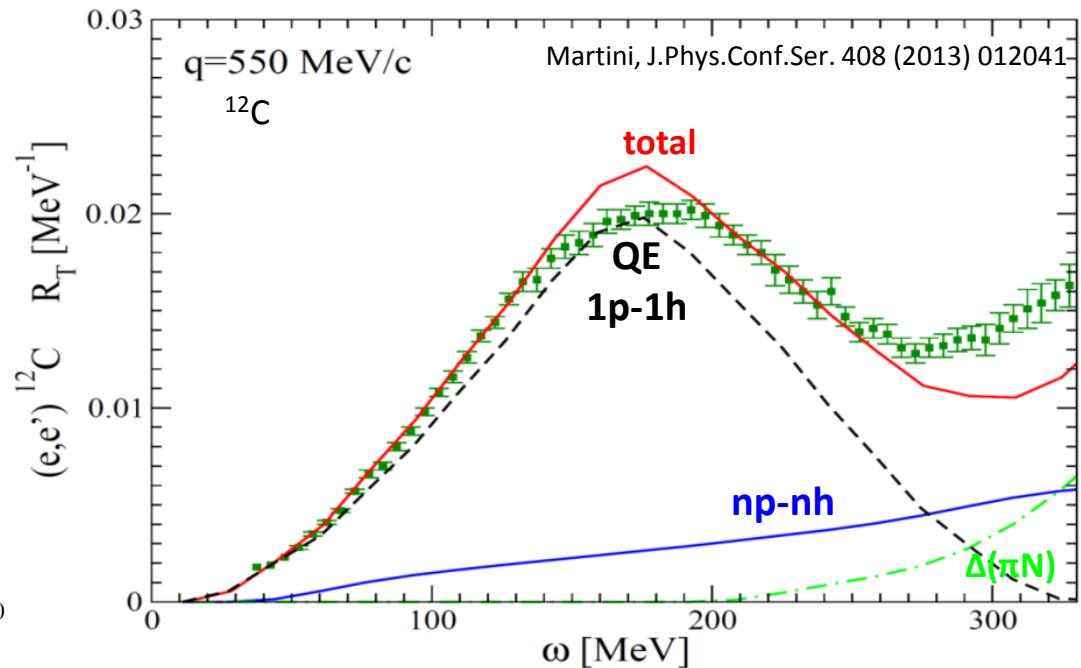
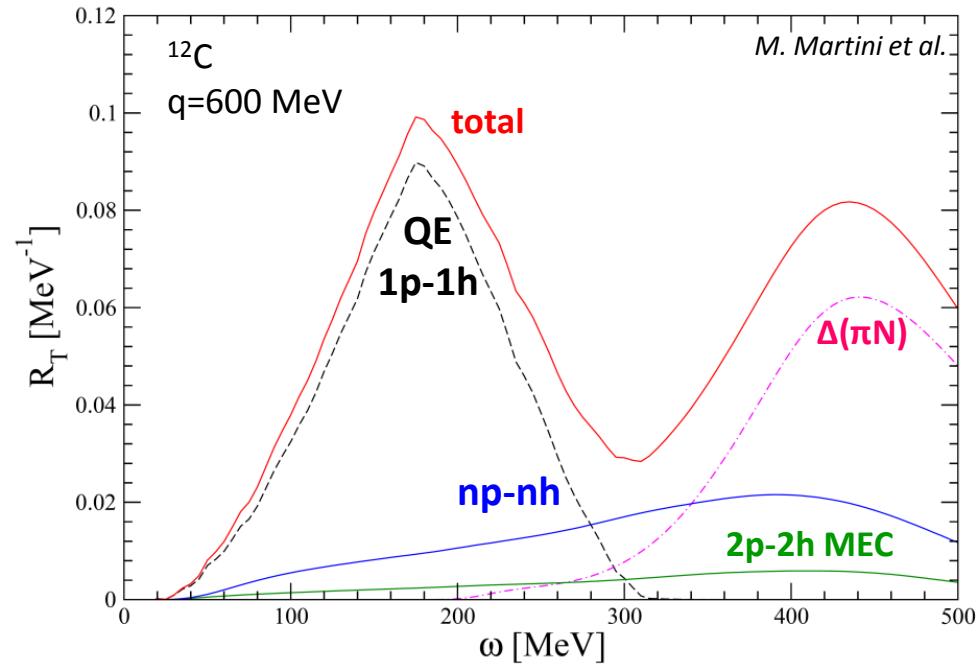
$$\begin{aligned} \frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} &= \frac{G_F^2 \cos^2 \theta_c}{2\pi^2} k' \epsilon' \cos^2 \frac{\theta}{2} \left[\frac{(q^2 - \omega^2)^2}{q^4} G_E^2 R_\tau + \frac{\omega^2}{q^2} G_A^2 R_{\sigma\tau(L)} + \right. \\ &\quad \left. + 2 \left(\tan^2 \frac{\theta}{2} + \frac{q^2 - \omega^2}{2q^2} \right) \left(G_M^2 \frac{\omega^2}{q^2} + G_A^2 \right) R_{\sigma\tau(T)} \pm 2 \frac{\epsilon + \epsilon'}{M_N} \tan^2 \frac{\theta}{2} G_A G_M R_{\sigma\tau(T)} \right] \end{aligned}$$

Nucleon properties → Form factors: Electric G_E , Magnetic G_M , Axial G_A

Nuclear dynamics → Nuclear Response Functions $R(q, \omega)$:

Isovector $R_\tau(\tau)$; Isospin Spin-Longitudinal $R_{\sigma\tau(L)}(\tau \sigma \cdot q)$; Isospin Spin Transverse $R_{\sigma\tau(T)}(\tau \sigma \times q)$

An example of nuclear response: Isospin Spin Transverse $R_{\sigma\tau(T)}$



$$\begin{aligned} \frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = & \frac{G_F^2 \cos^2 \theta_c}{2 \pi^2} k' \epsilon' \cos^2 \frac{\theta}{2} \left[\frac{(q^2 - \omega^2)^2}{q^4} G_E^2 R_\tau + \frac{\omega^2}{q^2} G_A^2 R_{\sigma\tau(L)} + \right. \\ & + 2 \left(\tan^2 \frac{\theta}{2} + \frac{q^2 - \omega^2}{2q^2} \right) \left(G_M^2 \frac{\omega^2}{q^2} + G_A^2 \right) \boxed{R_{\sigma\tau(T)}} \pm 2 \frac{\epsilon + \epsilon'}{M_N} \tan^2 \frac{\theta}{2} G_A G_M \boxed{R_{\sigma\tau(T)}} \left. \right] \end{aligned}$$

Form Factors

$$\begin{aligned} \frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = & \frac{G_F^2 \cos^2 \theta_c}{2 \pi^2} k' \epsilon' \cos^2 \frac{\theta}{2} \left[\frac{(q^2 - \omega^2)^2}{q^4} \underline{G_E^2} R_\tau + \frac{\omega^2}{q^2} \underline{G_A^2} R_{\sigma\tau(L)} + \right. \\ & + 2 \left(\tan^2 \frac{\theta}{2} + \frac{q^2 - \omega^2}{2q^2} \right) \left(\underline{G_M^2} \frac{\omega^2}{q^2} + \underline{G_A^2} \right) R_{\sigma\tau(T)} \pm 2 \frac{\epsilon + \epsilon'}{M_N} \tan^2 \frac{\theta}{2} \underline{G_A G_M} R_{\sigma\tau(T)} \left. \right] \end{aligned}$$

Standard dipole parameterization

Vector

$$\underline{G_E(Q^2)} = \underline{G_M(Q^2)} / (\mu_p - \mu_n) = (1 + Q^2 / M_V^2)^{-2}$$

$$Q^2 = q^2 - \omega^2$$

$$M_V = 0.84 \text{ GeV}/c^2$$

Axial

$$\underline{G_A(Q^2)} = g_A (1 + Q^2 / M_A^2)^{-2}$$

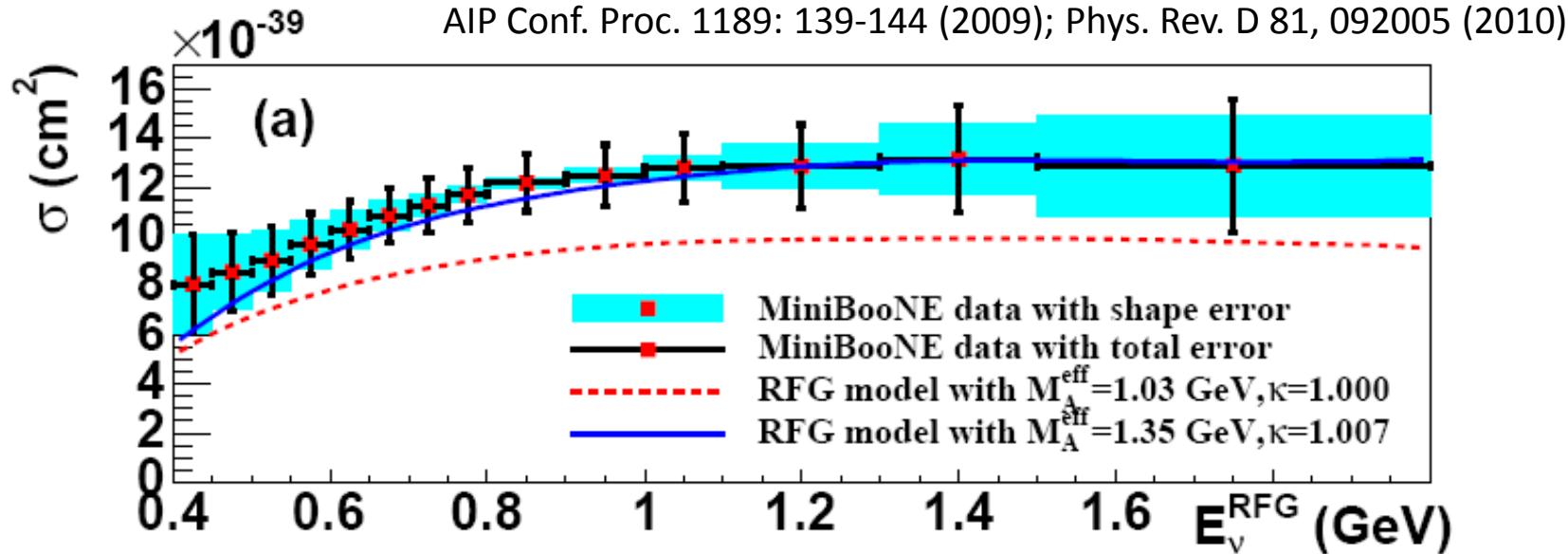
$$g_A = 1.26 \text{ from neutron } \beta \text{ decay}$$

$$M_A = (1.026 \pm 0.021) \text{ GeV}/c^2$$

from ν -deuterium CCQE and from π electroproduction

Quasielastic and MiniBooNE

MiniBooNE CC Quasielastic cross section on Carbon and the M_A puzzle



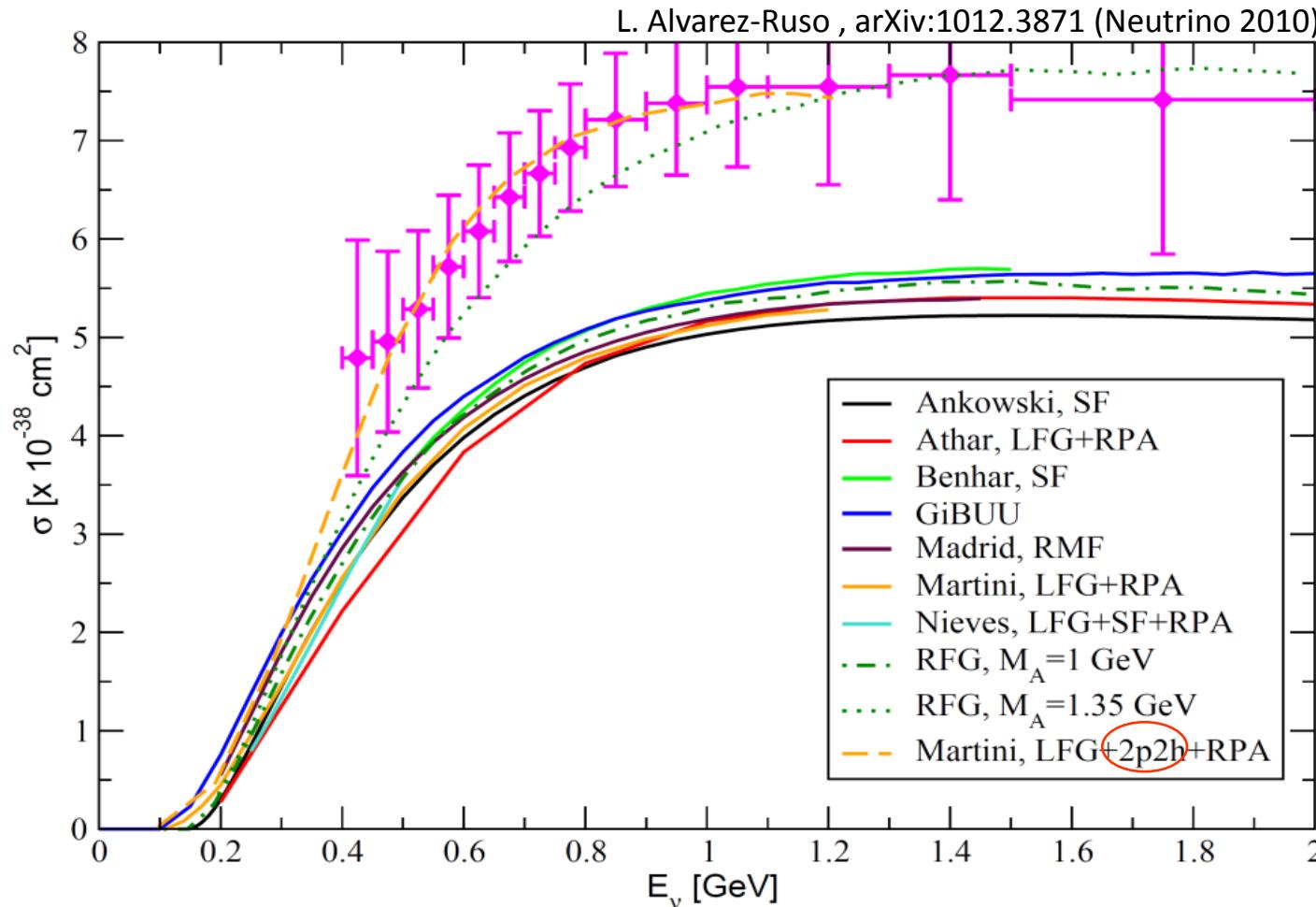
Comparison with a prediction based on RFG using $M_A=1.03 \text{ GeV}$ (standard value) reveals a discrepancy

In the Relativistic Fermi Gas (RFG) model an axial mass of 1.35 GeV is needed to account for data

p.s. Relativistic Fermi Gas: Nucleus as ensemble of non interacting fermions (nucleons)

puzzle??

Comparison of different theoretical models for Quasielastic



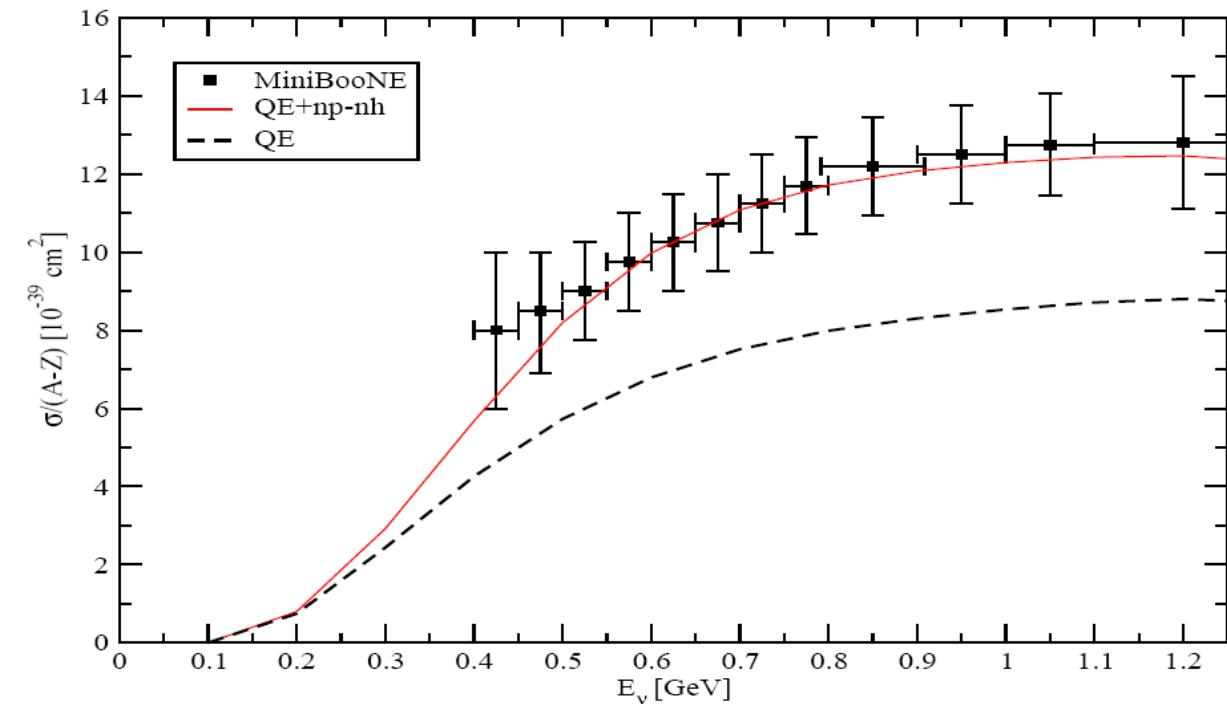
SF: Spectral Function
LFG: Local Fermi Gas
RPA: Random Phase Approximation
RMF: Relativistic Mean Field
GiBUU: Transport Equation

Comparison of models and Monte Carlo:
Boyd, Dytman, Hernandez, Sobczyk, Tacik ,
AIP Conf.Proc. 1189 (2009) 60-73

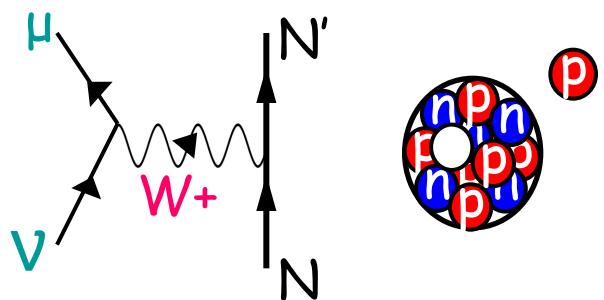
puzzle??

An explanation of this puzzle

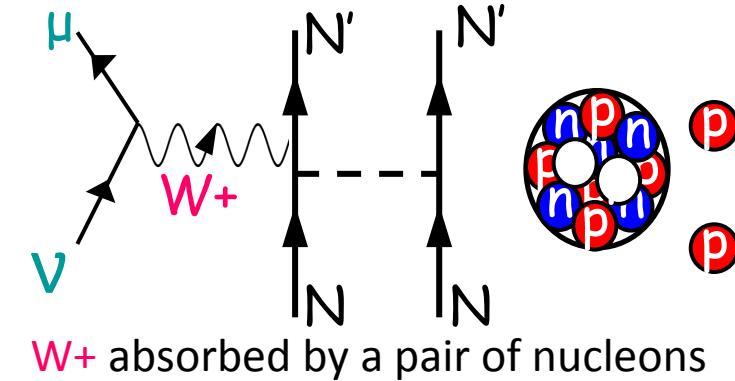
Inclusion of the multinucleon emission channel (np-nh)



Genuine CCQE



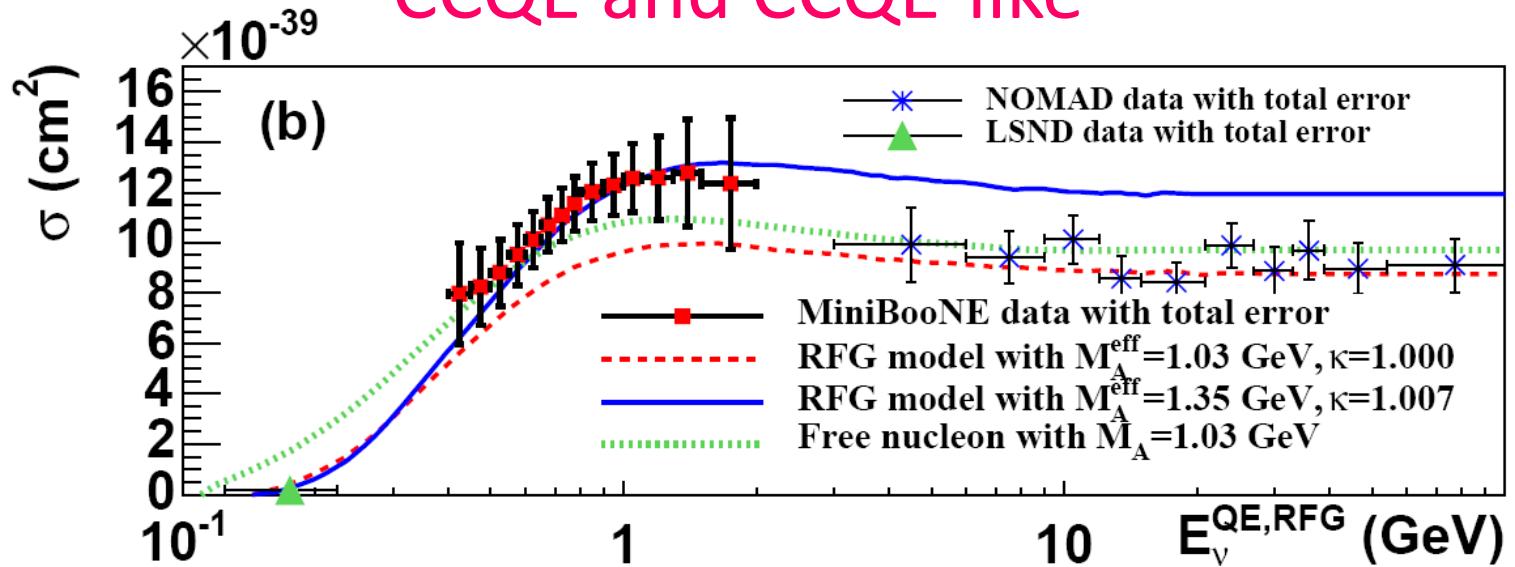
Two particles-two holes (2p-2h)



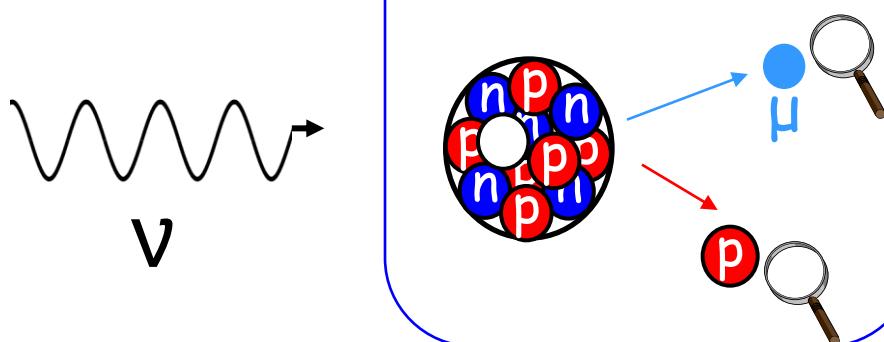
M. Martini, M. Ericson, G. Chanfray, J. Marteau Phys. Rev. C 80 065501 (2009)

Agreement with MiniBooNE without increasing M_A

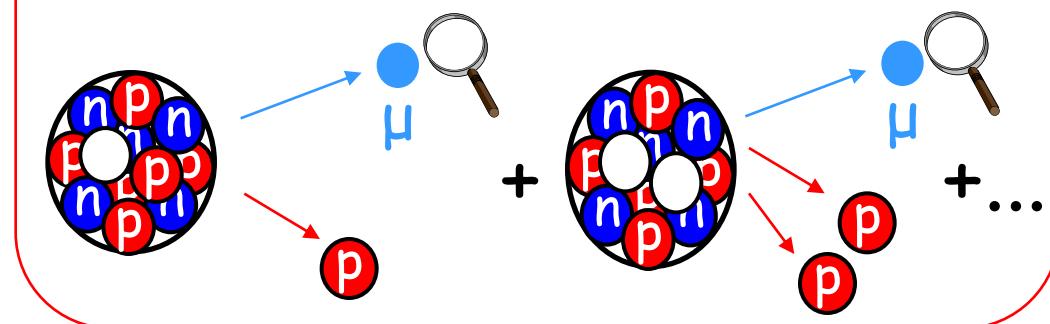
CCQE and CCQE-like



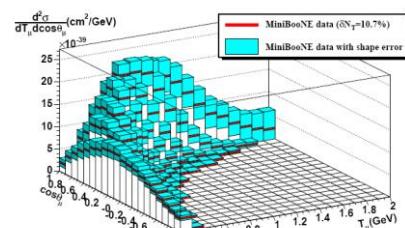
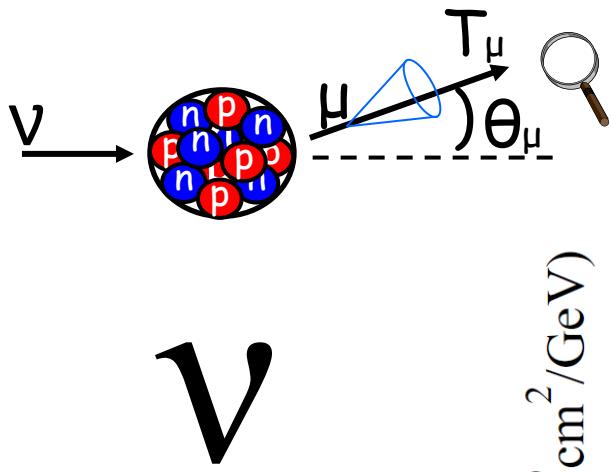
CCQE



CCQE-like
e.g. Cherenkov detectors

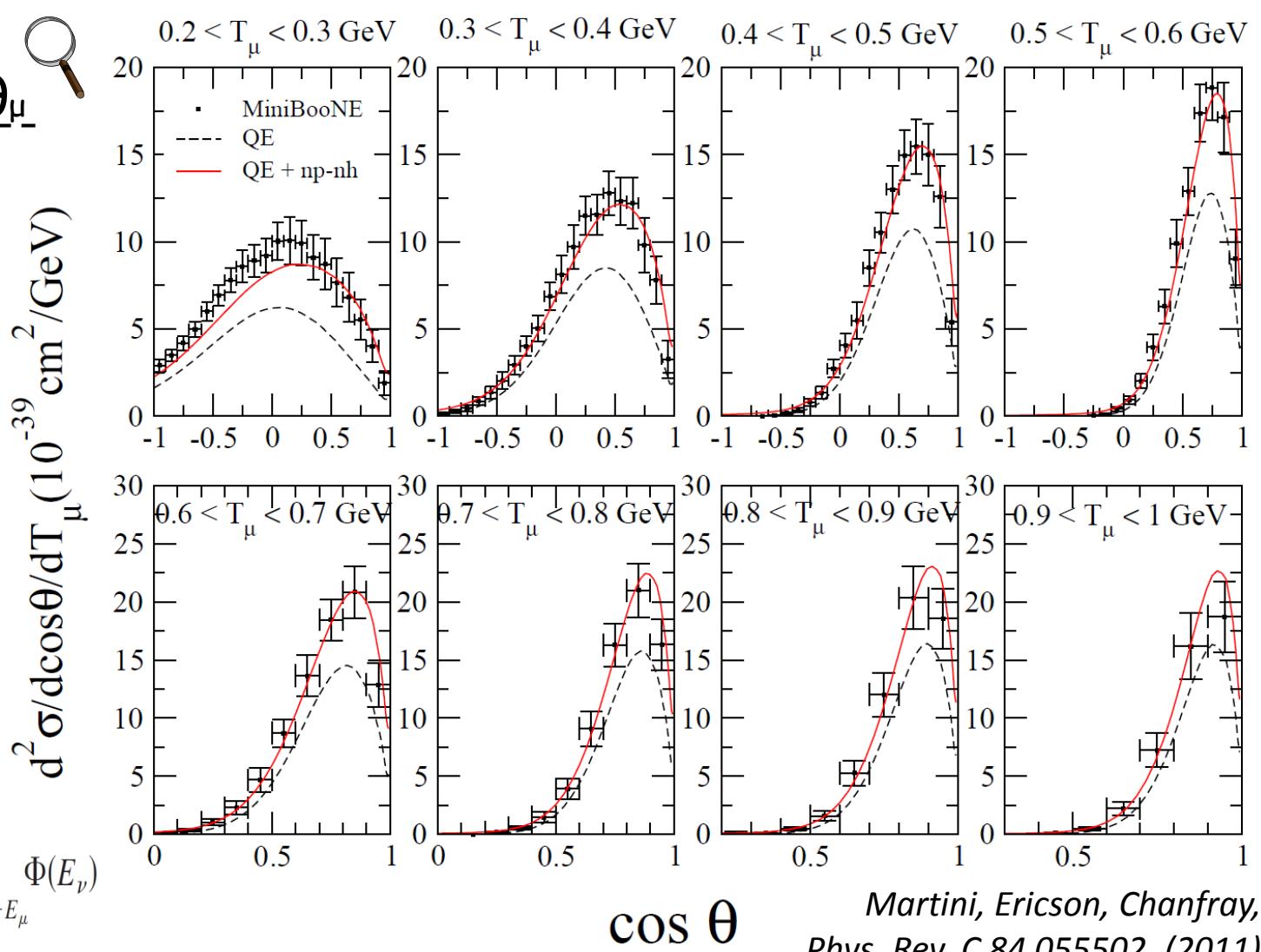


MiniBooNE CCQE-like flux-integrated double differential cross section



MiniBooNE, Phys. Rev. D 81, 092005 (2010)

$$\frac{d^2\sigma}{dE_\mu d\cos\theta} = \int dE_\nu \left[\frac{d^2\sigma}{d\omega d\cos\theta} \right]_{\omega=E_\nu - E_\mu} \Phi(E_\nu)$$

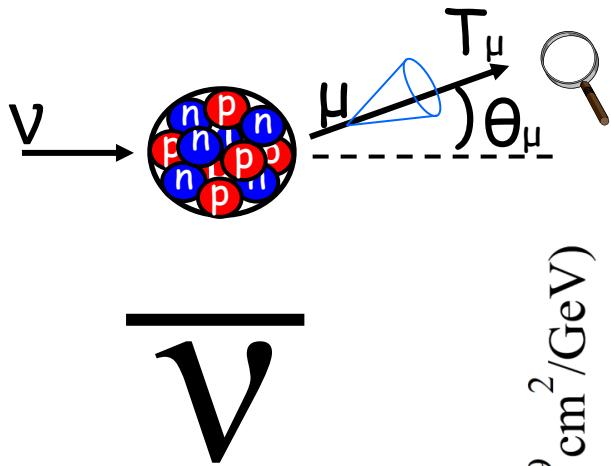


Martini, Ericson, Chanfray,
Phys. Rev. C 84 055502 (2011)

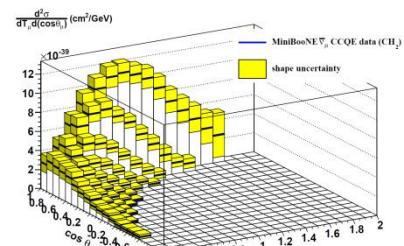
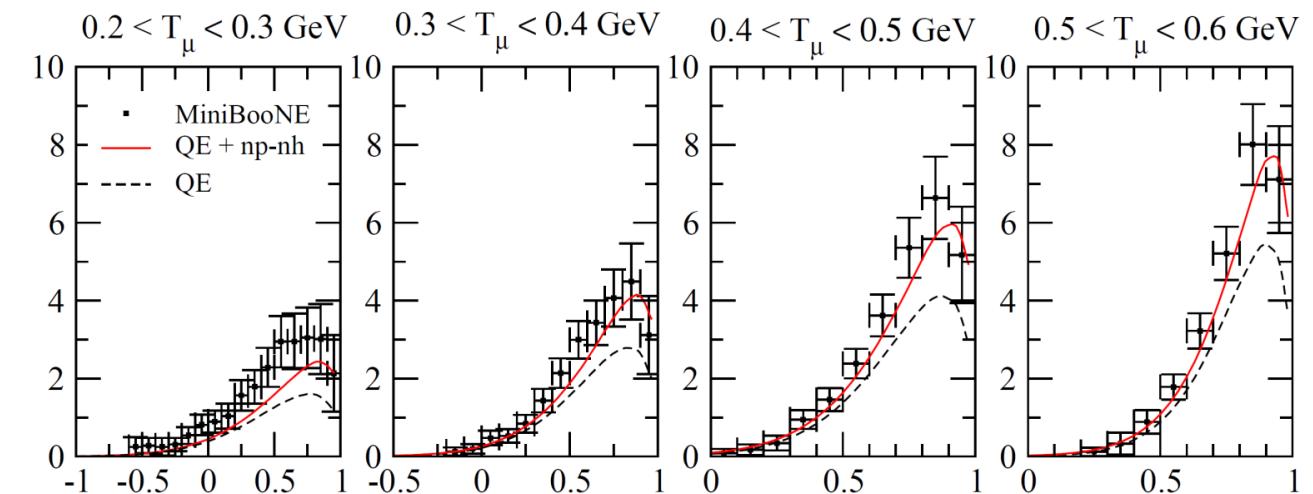
Agreement with MiniBooNE without increasing M_A once np-nh is included

Similar conclusions in Nieves et al. PLB 707, 72 (2012)

MiniBooNE CCQE-like flux-integrated double differential cross section

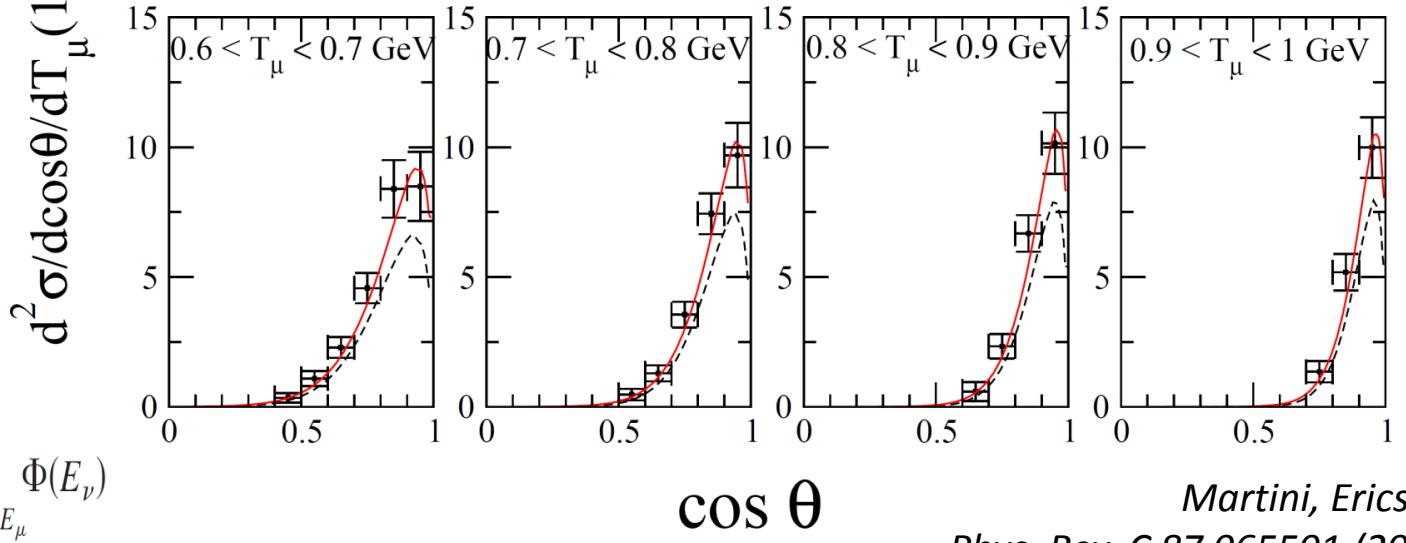


$$\frac{d^2\sigma}{dT_\mu d\cos\theta} (10^{-39} \text{ cm}^2/\text{GeV})$$



MiniBooNE, Phys. Rev. D 88 032001 (2013)

$$\frac{d^2\sigma}{dE_\mu d\cos\theta} = \int dE_\nu \left[\frac{d^2\sigma}{d\omega d\cos\theta} \right]_{\omega=E_\nu - E_\mu} \Phi(E_\nu)$$

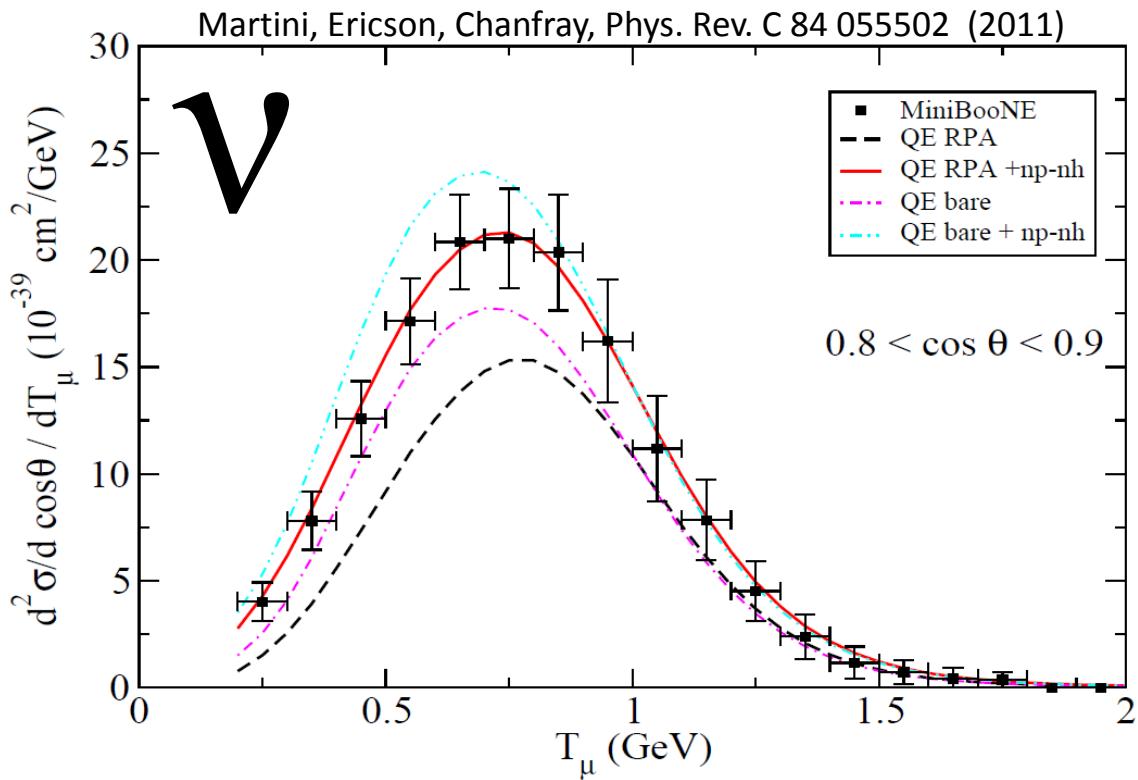


Martini, Ericson,
Phys. Rev. C 87 065501 (2013)

Agreement with MiniBooNE without increasing M_A once np-nh is included

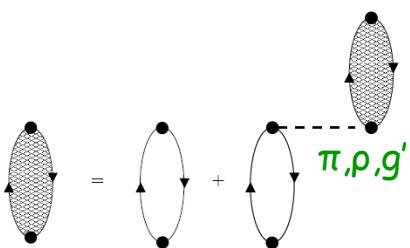
Similar conclusions in Nieves et al. PLB 721, 90 (2013)

Some considerations on the RPA + np-nh theoretical calculations



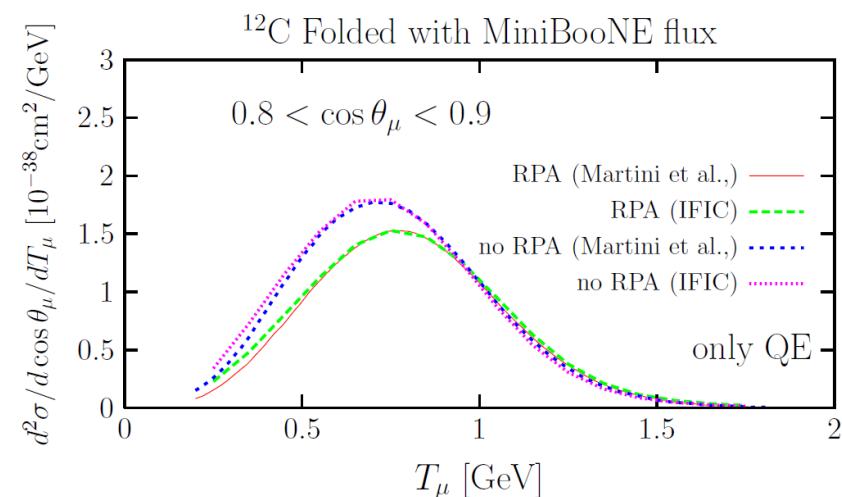
Delicate balance between
RPA quenching and np-nh enhancement

Random Phase Approximation (RPA)

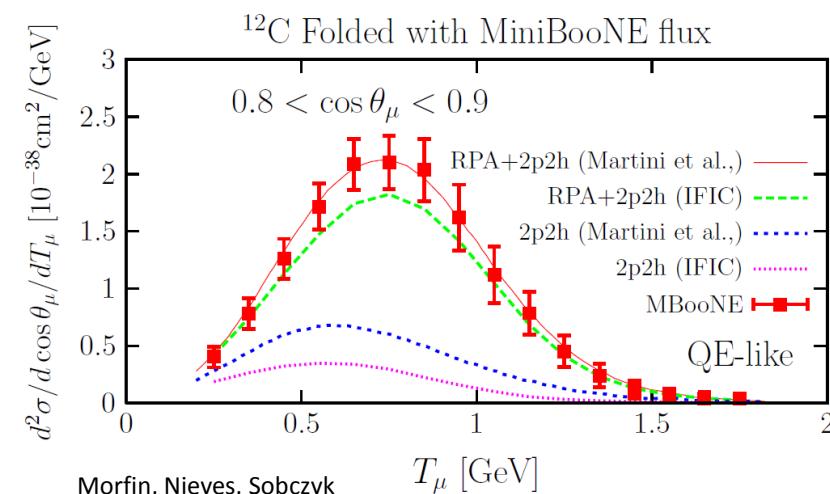


10/8/2015

M. Martini, NuFact15



- Genuine QE bare (RIFG) and RPA very similar in Martini et al. and Nieves et al.
- Differences for the np-nh contribution



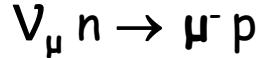
Morfin, Nieves, Sobczyk
Adv.High Energy Phys. (2012) 934597

15

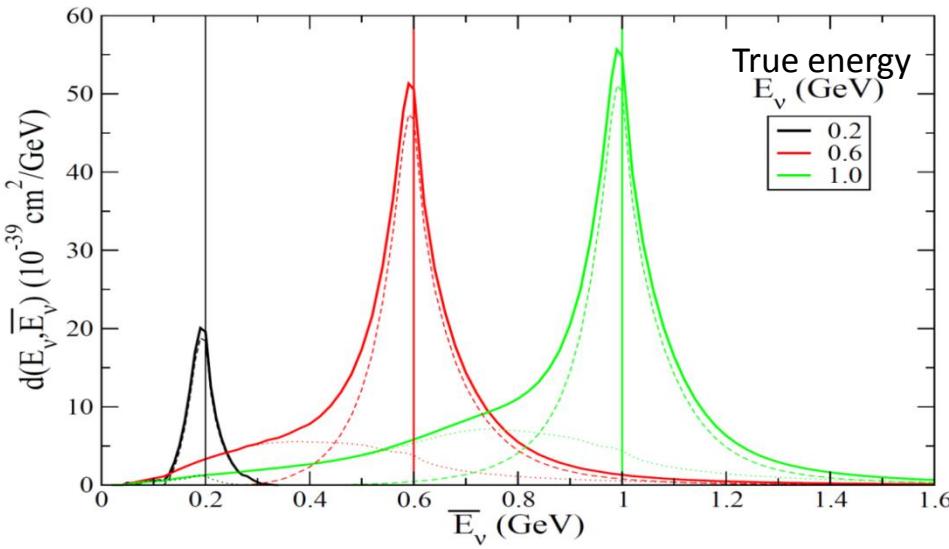
Neutrino energy reconstruction and neutrino oscillations

Reconstructed ν energy
(via two-body kinematics)

$$\overline{E}_\nu = \frac{E_\mu - m_\mu^2/(2M)}{1 - (E_\mu - P_\mu \cos \theta)/M}$$

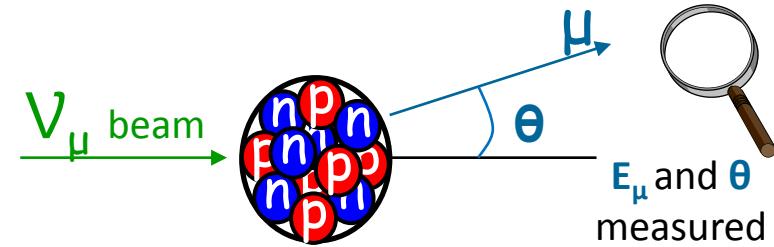


ν energy distribution

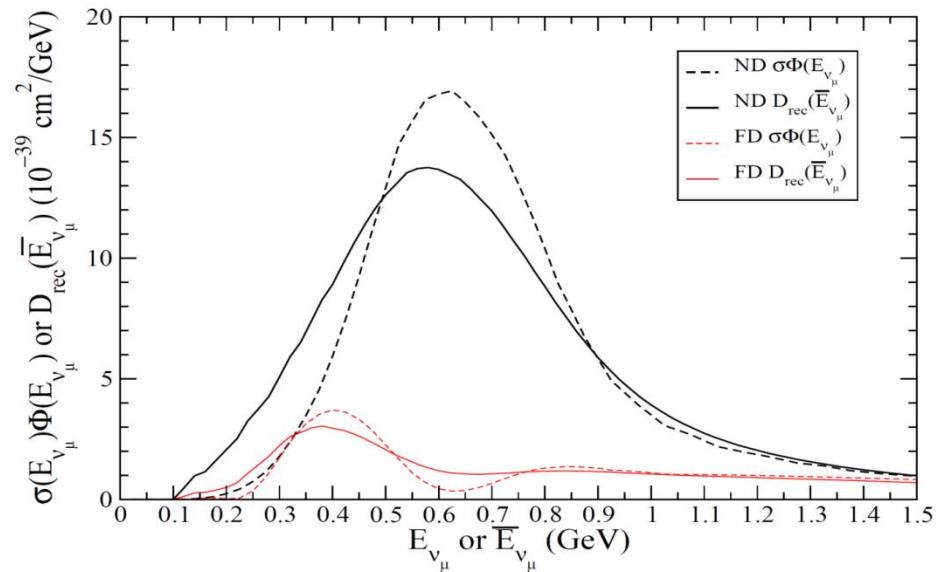


- Distributions not symmetrical around E_ν
- Crucial role of np-nh: low energy tail

M. Martini, M. Ericson, G. Chanfray, Phys. Rev. D 85 093012 (2012); Phys. Rev. D 87 013009 (2013)



ν_μ disappearance T2K



- Low energy enhancement
- Far Detector: middle hole largely filled

Neutrino energy reconstruction and neutrino oscillation analysis are affected by np-nh

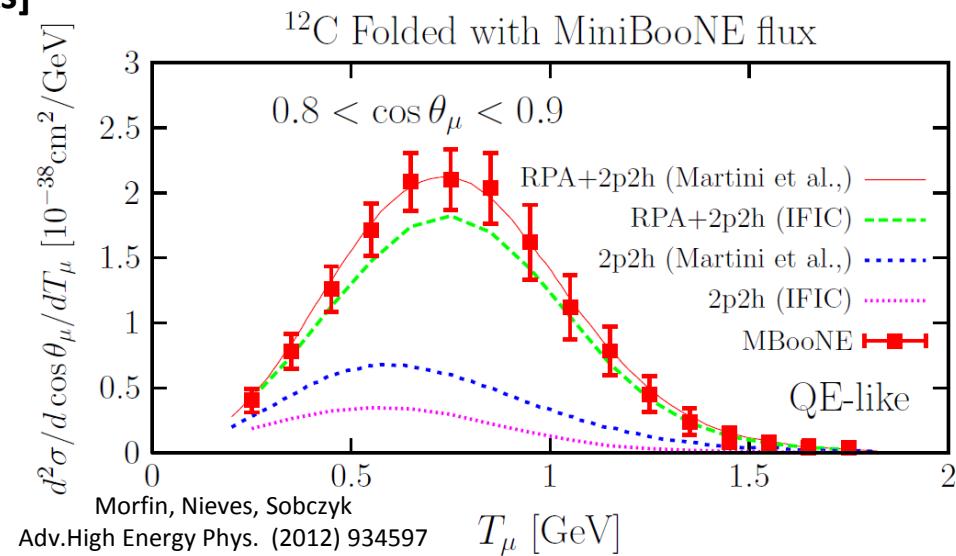
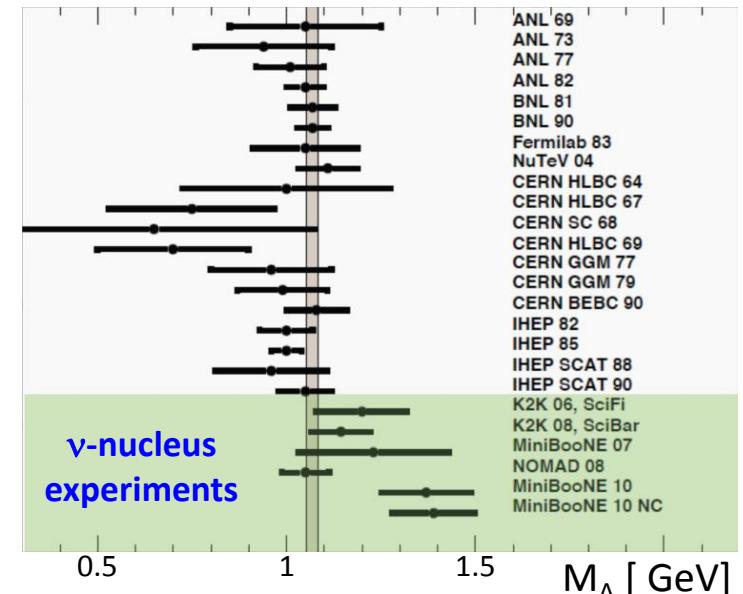
Similar results and conclusions in:

Nieves, Sanchez, Simo, Vicente Vacas Phys. Rev. D 85 113008 (2012); Lalakulich, Mosel, Gallmeister, Phys. Rev. C 86 054606 (2012)

The multinucleon emission channel (or np-nh, or 2p-2h)

- A lot of interest in these last years
- Explanation of the axial mass puzzle
- It was not included in the generators used for the analyses of ν cross sections and oscillations experiments
- Neutrino energy reconstruction and neutrino oscillation analysis are affected by np-nh
- Today there is an effort to include this np-nh channel in several Monte Carlo [H. Gallagher and T. Feusels talks]
- Several theoretical calculations agree on its crucial role but there are some differences on the results obtained for this channel

[In the following I will focus essentially on this channel]



Theoretical calculations on np-nh contributions to ν -nucleus cross sections

M. Martini, M. Ericson, G. Chanfray, J. Marteau (Lyon, IPNL)

Phys. Rev. C 80 065501 (2009) ν σ_{total}

Phys. Rev. C 81 045502 (2010) ν vs antiv (σ_{total})

Phys. Rev. C 84 055502 (2011) ν $d^2\sigma$, $d\sigma/dQ^2$

Phys. Rev. D 85 093012 (2012) impact of np-nh on ν energy reconstruction

Phys. Rev. D 87 013009 (2013) impact of np-nh on ν energy reconstruction and ν oscillation

Phys. Rev. C 87 065501 (2013) antiv $d^2\sigma$, $d\sigma/dQ^2$

Phys. Rev. C 90 025501 (2014) inclusive ν $d^2\sigma$

Phys. Rev. C 91 035501 (2015) combining ν and antiv $d^2\sigma$, $d\sigma/dQ^2$

J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas, F. Sanchez, R. Gran (Valencia, IFIC)

Phys. Rev. C 83 045501 (2011) ν , antiv σ_{total}

Phys. Lett. B 707 72-75 (2012) ν $d^2\sigma$

Phys. Rev. D 85 113008 (2012) impact of np-nh on ν energy reconstruction

Phys. Lett. B 721 90-93 (2013) antiv $d^2\sigma$

Phys. Rev. D 88 113007 (2013) extension of np-nh up to 10 GeV

J.E. Amaro, M.B. Barbaro, T.W. Donnelly, G. Megias, I. Ruiz Simo et al. (Superscaling)

Phys. Lett. B 696 151-155 (2011) ν $d^2\sigma$

Phys. Rev. D 84 033004 (2011) ν $d^2\sigma$, σ_{total}

Phys. Rev. Lett. 108 152501 (2012) antiv $d^2\sigma$, σ_{total}

Phys. Rev. D 90 033012 (2014) 2p-2h phase space

Phys. Rev. D 90 053010 (2014) angular distribution

Phys. Rev. D 91 073004 (2015) parametrization of vector MEC

arXiv 1506.00801 (2015) inclusive ν $d^2\sigma$

Two-body contributions to sum rules and responses in the electroweak sector

A. Lovato, S. Gandolfi, J. Carlson, S. C. Pieper, R. Schiavilla (Ab-initio many-body)

Phys. Rev. Lett. 112 182502 (2014) [12C sum rules for Neutral Current](#)

Phys. Rev. C 91 062501 (2015) [4He and 12C responses for Neutral Current](#)

Effective models taking into account np-nh excitations

O. Lalakulich, K. Gallmeister and U. Mosel (GiBUU)

Phys. Rev. C 86 014614 (2012) [ν σtotal, \$d^2\sigma\$, \$d\sigma/dQ^2\$](#)

Phys. Rev. C 86 054606 (2012) [impact of np-nh on ν energy reconstruction and ν oscillation](#)

Phys. Rev. Lett. 112 151802 (2014) [energy reconstruction in LBNE](#)

Phys. Rev. D 89 093003 (2014) [reaction mechanisms at MINERvA](#)

A. Bodek, H.S. Budd, M.E. Christy (Transverse Enhancement Model)

EPJ C 71 1726 (2011) [ν and antiv σtotal, \$d\sigma/dQ^2\$](#)

$$G_{Mp}^{nuclear}(Q^2) = G_{Mp}(Q^2) \times \sqrt{1 + AQ^2 e^{-Q^2/B}}$$

np-nh work in progress: generalization to ν of approaches used for e scattering

O. Benhar, A. Lovato, N. Rocco

Phys. Rev. C 92, 024602 (2015) [Factorization ansatz and two-nucleon spectral function](#)

T. Van Cuyck, N. Jachowicz, J. Ryckebusch et al. (Ghent) [\[T. Van Cuyck talk\]](#)

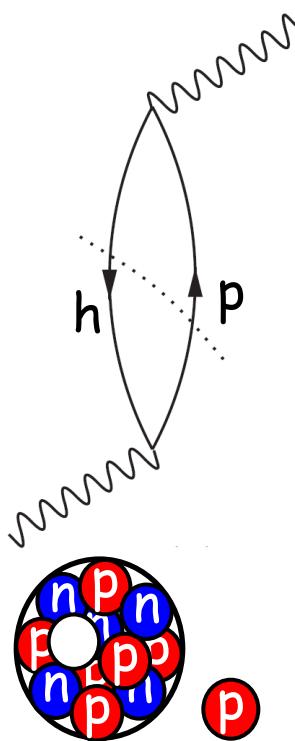
np – nh excitations in the Monte Carlo generators

[\[H. Gallagher and T. Feusels talks\]](#)

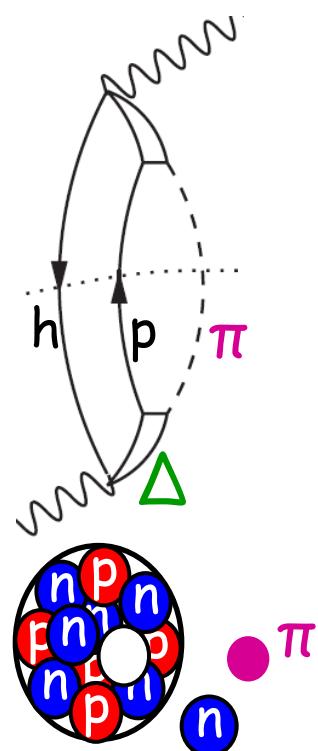
Some theoretical details

Nuclear Response Functions

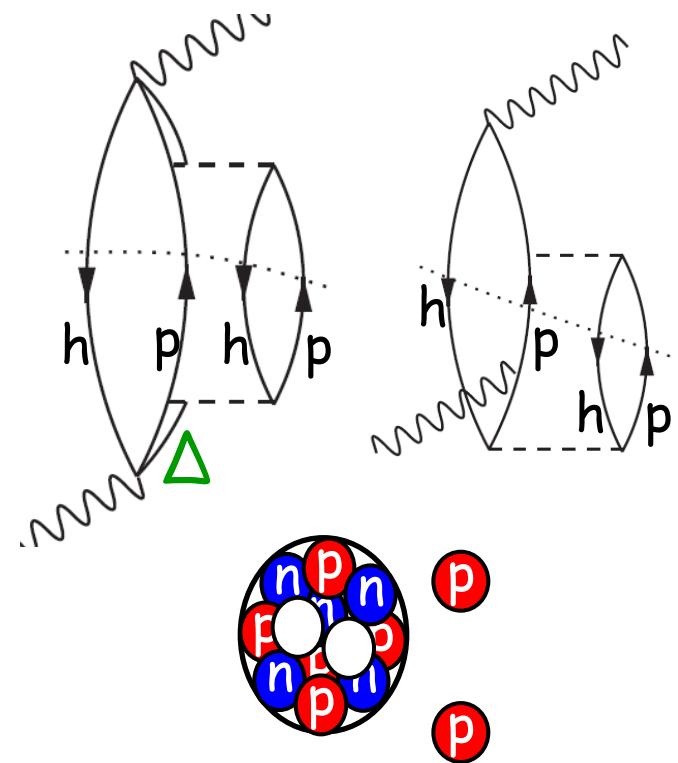
1p-1h
QE



1p-1h
1 π production



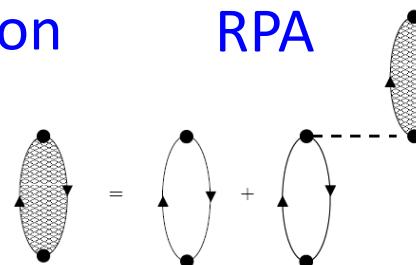
2p-2h:
two examples



Nuclear response in Random Phase Approximation

(the approach used by Martini et al. and Nieves et al.)

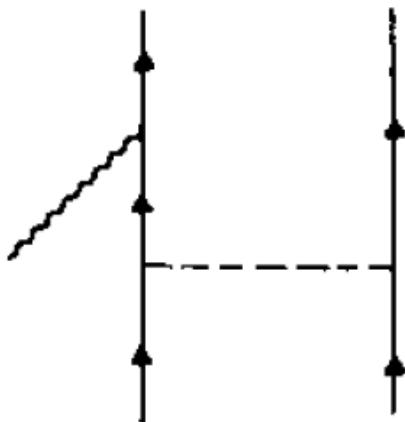
RPA



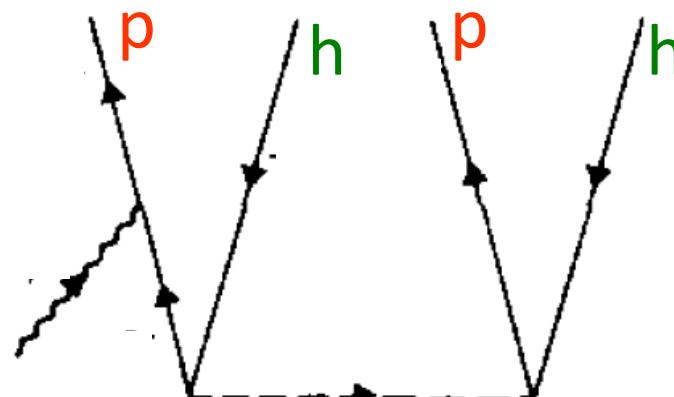
Two particle-two hole sector (2p-2h)

Three equivalent representations of the same process

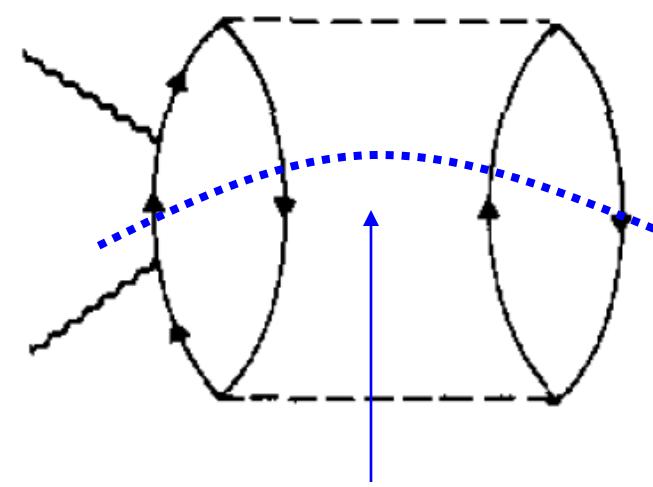
2 body current



2p-2h matrix element



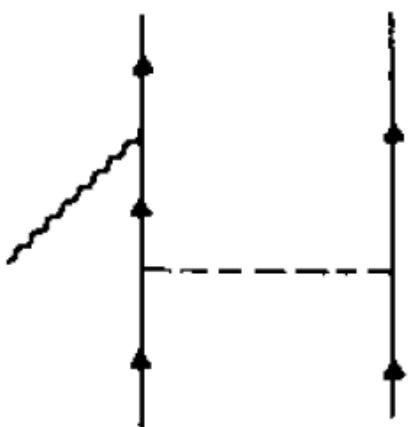
2p-2h response



Final state: two particles-two holes

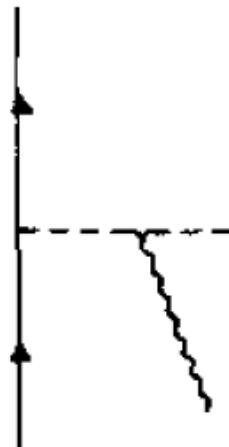
Some diagrams for 2 body currents

Nucleon-Nucleon
correlations

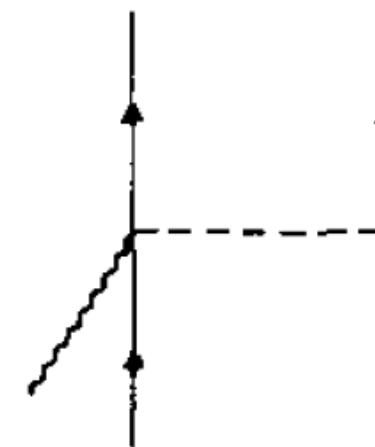


J^{corr}

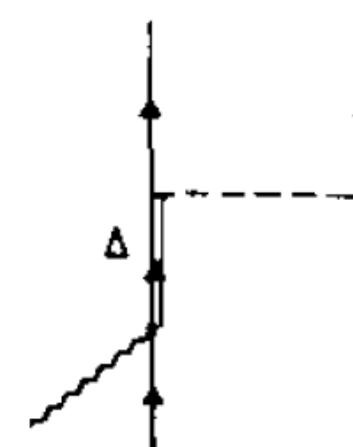
Meson Exchange Currents (MEC)



Pion in flight



Contact

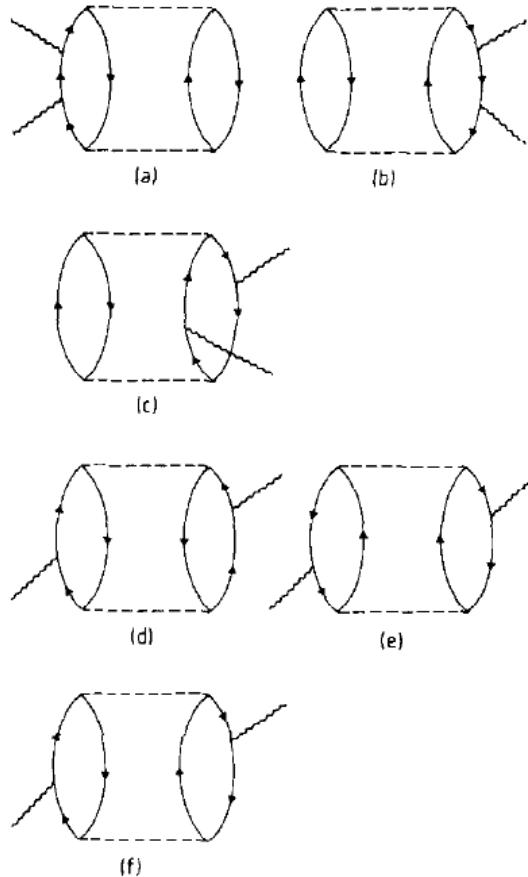


Delta

J^{MEC}

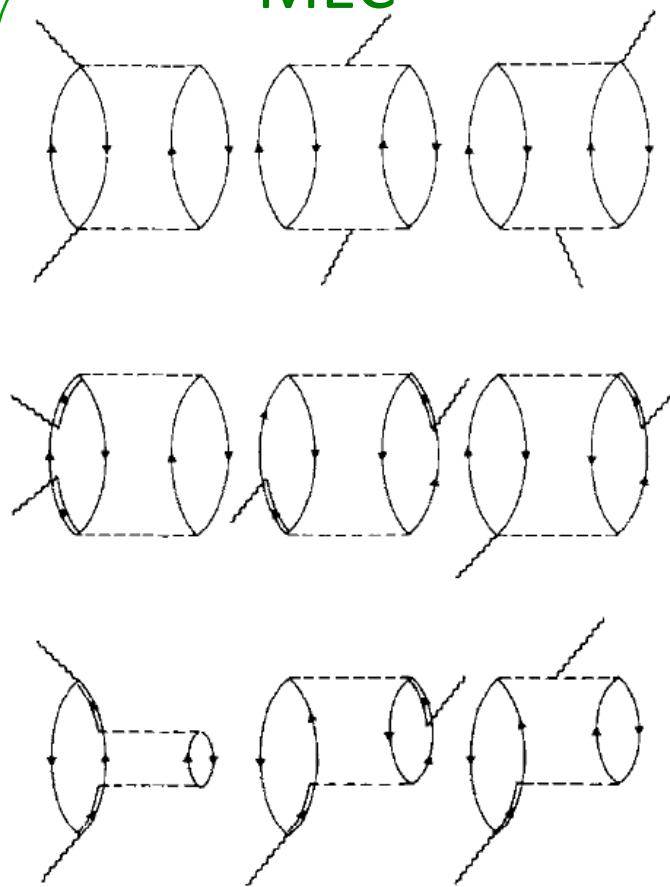
Some diagrams for 2p-2h responses

NN correlations



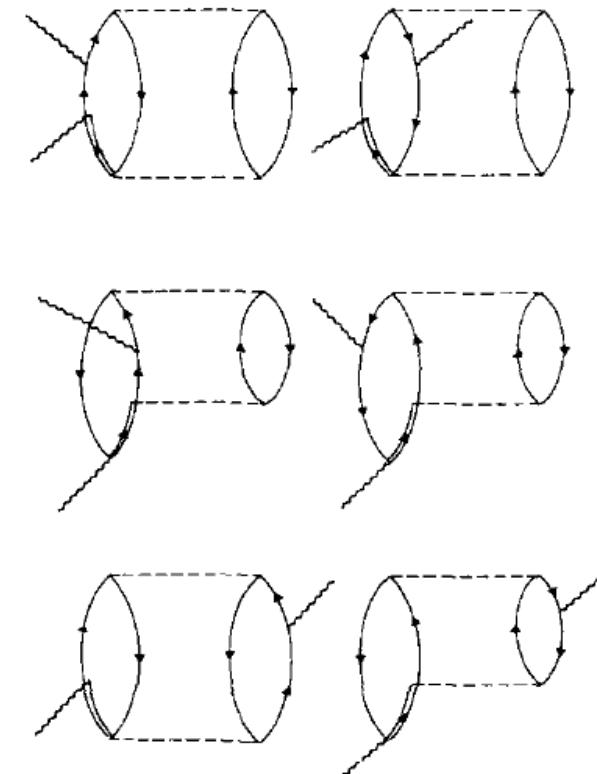
16 diagrams

MEC



49 diagrams

NN correlation-MEC interference



56 diagrams

Main difficulties in the 2p-2h sector

$$W_{2p-2h}^{\mu\nu}(\mathbf{q}, \omega) = \frac{V}{(2\pi)^9} \int d^3p'_1 d^3p'_2 d^3h_1 d^3h_2 \frac{m_N^4}{E_1 E_2 E'_1 E'_2} \theta(p'_2 - k_F) \theta(p'_1 - k_F) \theta(k_F - h_1) \theta(k_F - h_2) \\ \langle 0 | J^\mu | \mathbf{h}_1 \mathbf{h}_2 \mathbf{p}'_1 \mathbf{p}'_2 \rangle \langle \mathbf{h}_1 \mathbf{h}_2 \mathbf{p}'_1 \mathbf{p}'_2 | J^\nu | 0 \rangle \delta(E'_1 + E'_2 - E_1 - E_2 - \omega) \delta(\mathbf{p}'_1 + \mathbf{p}'_2 - \mathbf{h}_1 - \mathbf{h}_2 - \mathbf{q})$$

- 7-dimensional integrals $\int d^3h_1 d^3h_2 d\theta'_1$ of thousands of terms
- Huge number of diagrams and terms
 - e.g. fully relativistic calculation (**just of MEC !**):
3000 direct terms More than 100 000 exchange terms
De Pace, Nardi, Alberico, Donnelly, Molinari, Nucl. Phys. A741, 249 (2004)
- Divergences (angular distribution; NN correlations contributions)
- Calculations for all the kinematics compatible with the experimental neutrino flux

Computing very demanding

Hence different approximations by different groups:

- choice of subset of diagrams and terms;
- different prescriptions to regularize the divergences;
- reduce the dimension of the integrals (7D \rightarrow 2D if non relativistic; 7D \rightarrow 1D if $h_1 = h_2 = 0$)

\Rightarrow Different final results

Analogies and differences of 2p-2h

M. Martini, M. Ericson, G. Chanfray, J. Marteau

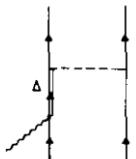
[Genuine QE (1 body contribution): LRGF+RPA]

NN correlations

Δ -MEC

NN correlations - MEC interference

Axial and Vector



π, g'

J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas et al.

[Genuine QE (1 body contribution): LRGF+SF+RPA]

NN correlations

MEC

NN correlations - MEC interference

Axial and Vector

π

J.E. Amaro, M.B. Barbaro, T.W. Donnelly, G. Megias, I. Ruiz Simo et al.

[Genuine QE (1 body contribution): Superscaling]

Only Vector

MEC

[Generalization to axial in progress]

[Inclusion of NN corr. and corr.-MEC Interf. in progress (already studied for the electron scattering)]

A. Lovato, S. Gandolfi, J. Carlson, S. C. Pieper, R. Schiavilla

[Genuine QE (1 body contribution): GFMC with AV18 and IL7 potentials]

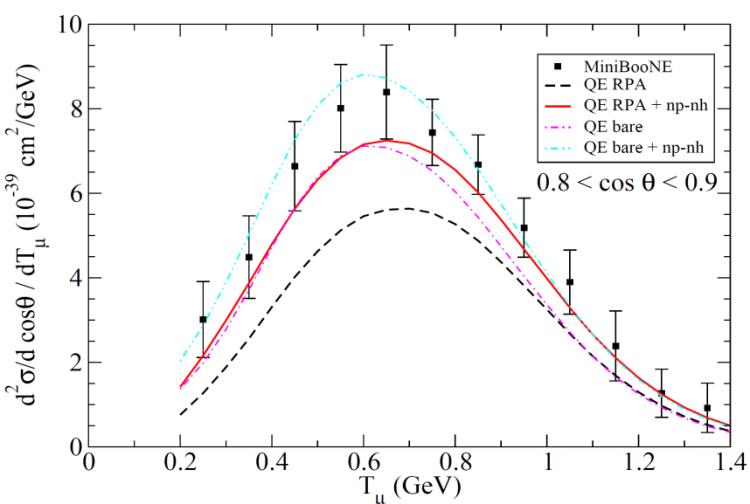
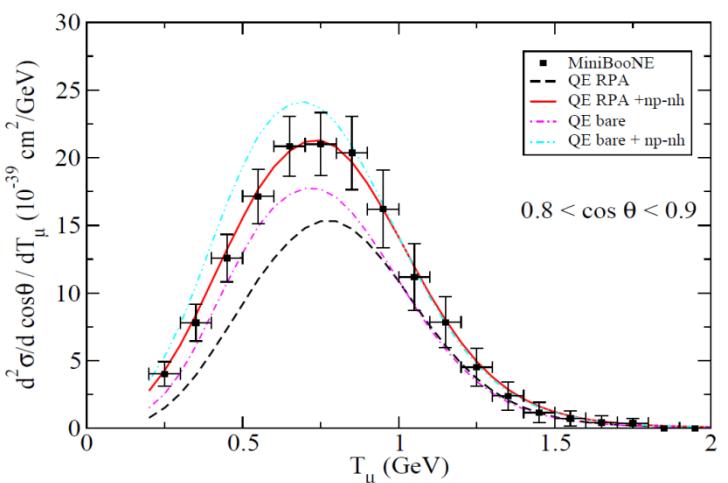
NN correlations

MEC

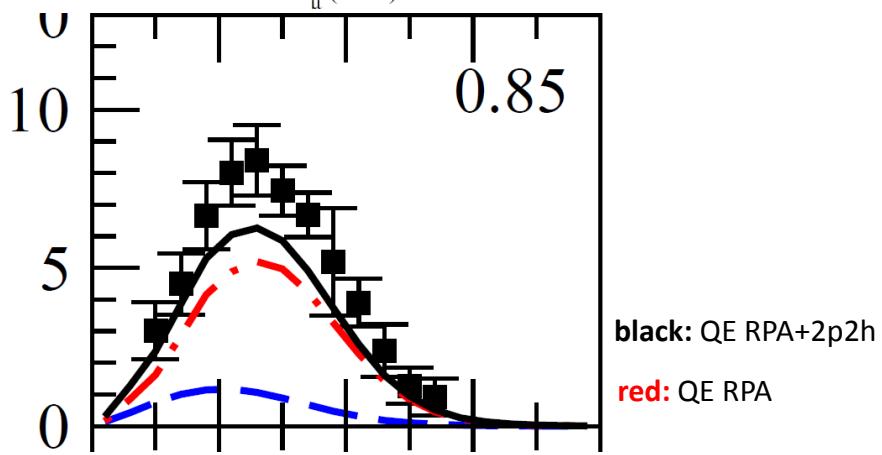
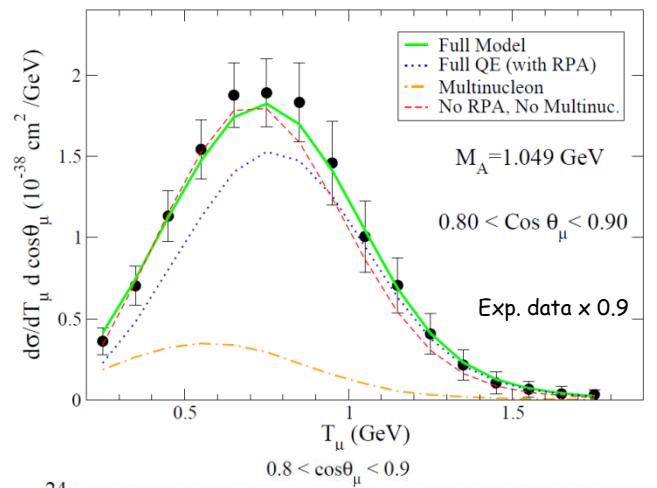
NN correlations - MEC interference

Axial and Vector

Martini et al.

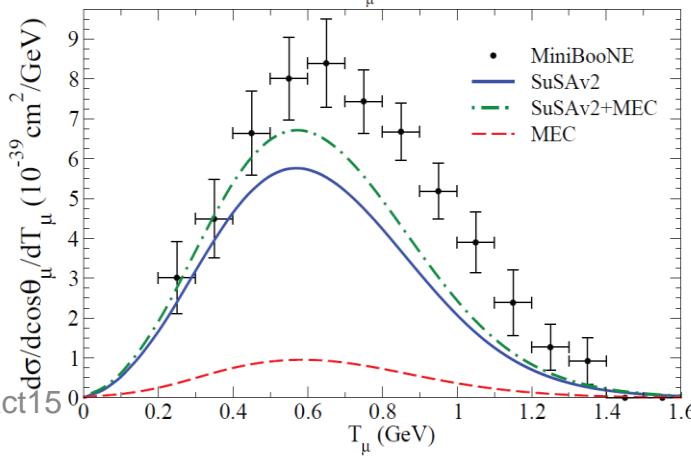
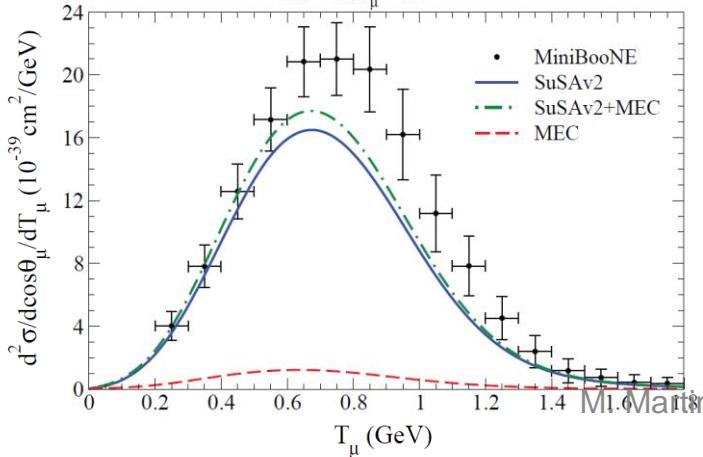


Nieves et al.



Amaro et al.

[Megias talk]



Neutrino vs Antineutrino interactions and CP violation

Detection of an asymmetry between ν and $\text{anti}\nu$ oscillation rates as evidence of CP violation

$$\nu_\mu \rightarrow \nu_e \quad \text{vs} \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$$\begin{aligned} \frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = & \frac{G_F^2 \cos^2 \theta_c}{2\pi^2} k' \epsilon' \cos^2 \frac{\theta}{2} \left[\frac{(q^2 - \omega^2)^2}{q^4} G_E^2 R_\tau + \frac{\omega^2}{q^2} G_A^2 R_{\sigma\tau(L)} + \right. \\ & + 2 \left(\tan^2 \frac{\theta}{2} + \frac{q^2 - \omega^2}{2q^2} \right) \left(G_M^2 \frac{\omega^2}{q^2} + G_A^2 \right) R_{\sigma\tau(T)} \left. \pm 2 \frac{\epsilon + \epsilon'}{M_N} \tan^2 \frac{\theta}{2} G_A G_M R_{\sigma\tau(T)} \right] \end{aligned}$$

Vector-Axial interference:

basic asymmetry from weak interaction theory

Vector-Axial interference

$$\left\{ \begin{array}{ll} + & (\nu) \\ - & (\bar{\nu}) \end{array} \right.$$

The ν and anti ν interactions differ by the sign of the V-A interference term

- the relative weight of the different nuclear responses is different for neutrinos and antineutrinos
- the relative role of 2p-2h contributions is different for neutrinos and antineutrinos



Nuclear effects generate an asymmetry unrelated to CP violation
which has to be fully mastered

Where 2p-2h contributions enter in the different approaches

Martini et al.

Nieves et al.

Amaro et al.

Lovato et al.

Bodek et al.

[Follow the color and the style of the lines:]

$$\begin{aligned} \frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = & \frac{G_F^2 \cos^2 \theta_c}{2 \pi^2} k' \epsilon' \cos^2 \frac{\theta}{2} \left[\frac{(q^2 - \omega^2)^2}{q^4} G_E^2 R_\tau \right. \\ & + \left. \frac{\omega^2}{q^2} G_A^2 R_{\sigma\tau(L)} \right. \\ & + 2 \left(\tan^2 \frac{\theta}{2} + \frac{q^2 - \omega^2}{2q^2} \right) \left(G_M^2 \frac{\omega^2}{q^2} + G_A^2 \right) R_{\sigma\tau(T)} \pm 2 \frac{\epsilon + \epsilon'}{M_N} \tan^2 \frac{\theta}{2} G_A G_M R_{\sigma\tau(T)} \left. \right] \end{aligned}$$

An example of difference:

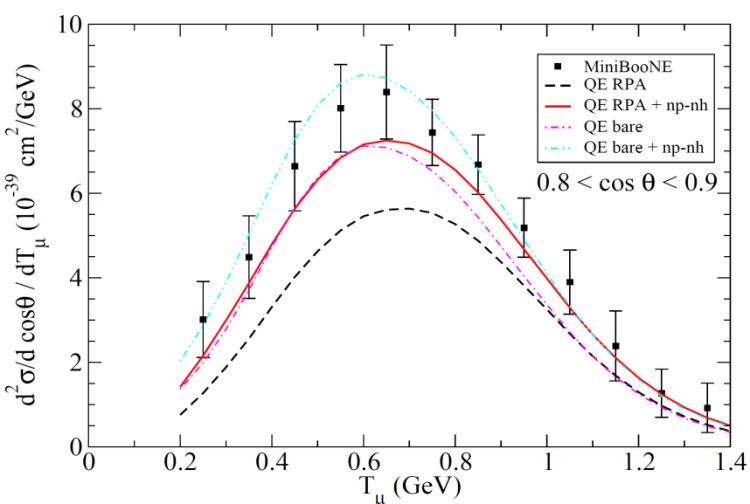
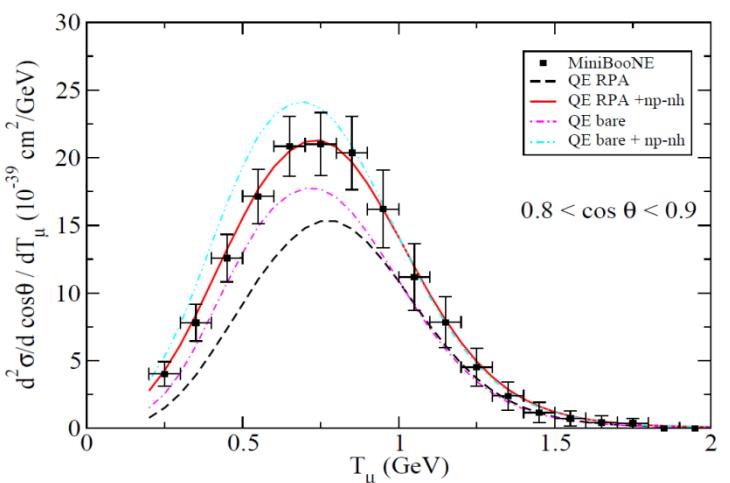
in Amaro et al. there are no 2p-2h in the axial and vector-axial interference terms

→the relative role of 2p-2h contributions for neutrinos and antineutrinos is different in the different approaches

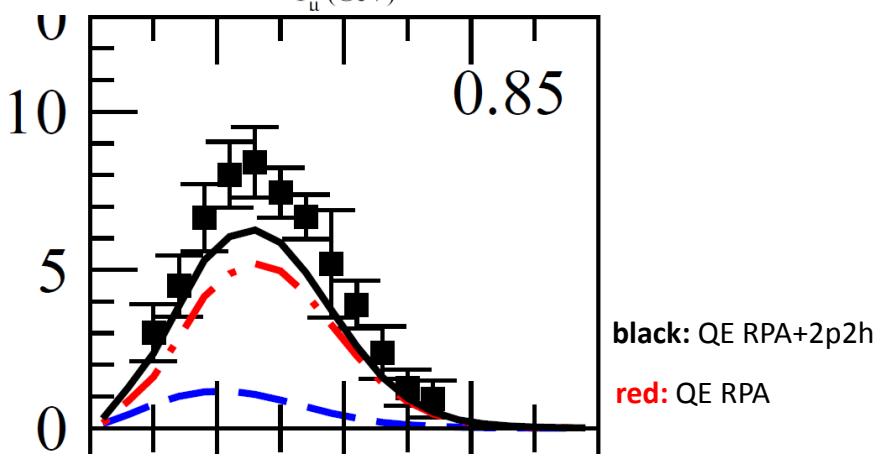
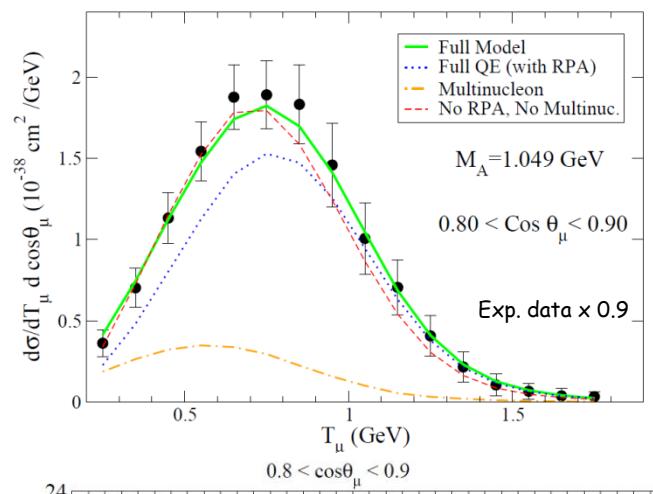
V

V

Martini et al.

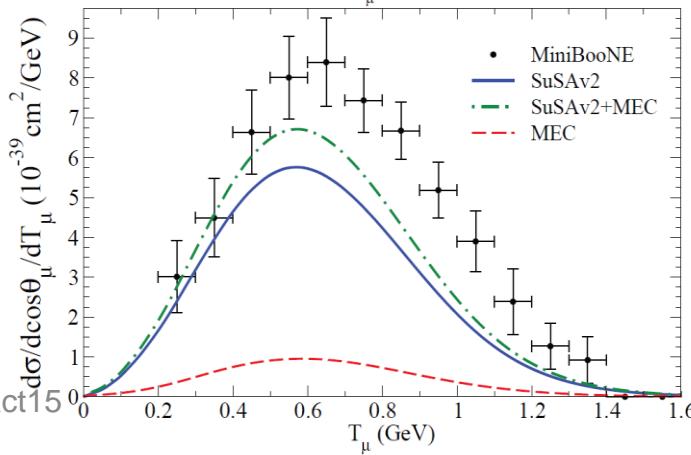
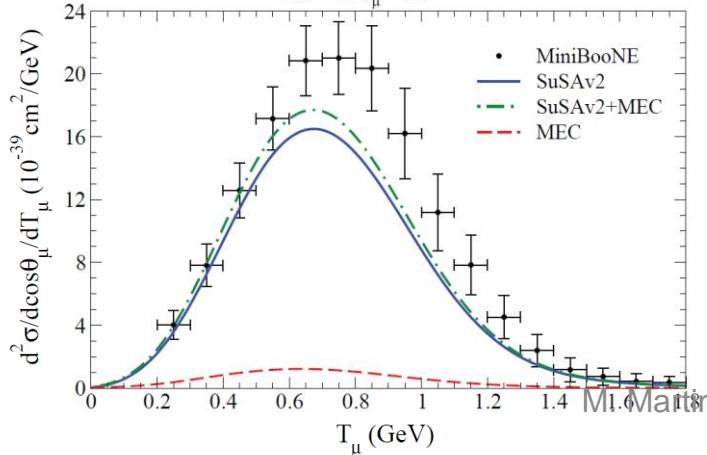


Nieves et al.



Amaro et al.

[Megias talk]



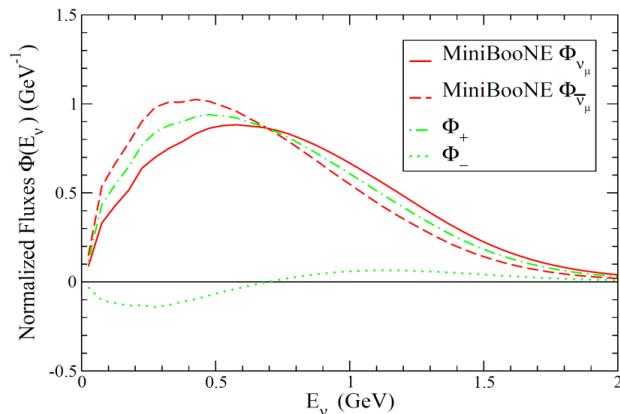
Difference of ν and antiv cross sections and the VA interference term

$$d\sigma \sim d\sigma_L + d\sigma_T \pm d\sigma_{VA}$$

$$d\sigma_\nu - d\sigma_{\bar{\nu}} \xrightarrow{?} 2d\sigma_{VA}$$

Difference gives only the VA term for identical ν and antiv flux

Problem: flux dependence of $d\sigma$ $\frac{d^2\sigma}{dE_\mu d\cos\theta} = \int dE_\nu \left[\frac{d^2\sigma}{d\omega d\cos\theta} \right]_{\omega=E_\nu - E_\mu} \Phi(E_\nu)$



We introduce the **mean flux**

$$\Phi_+ = 1/2[\Phi_\nu + \Phi_{\bar{\nu}}]$$

We calculate the difference using **real** and **mean** MiniBooNE fluxes results

The mean flux contribution is dominant in the ν antiv difference

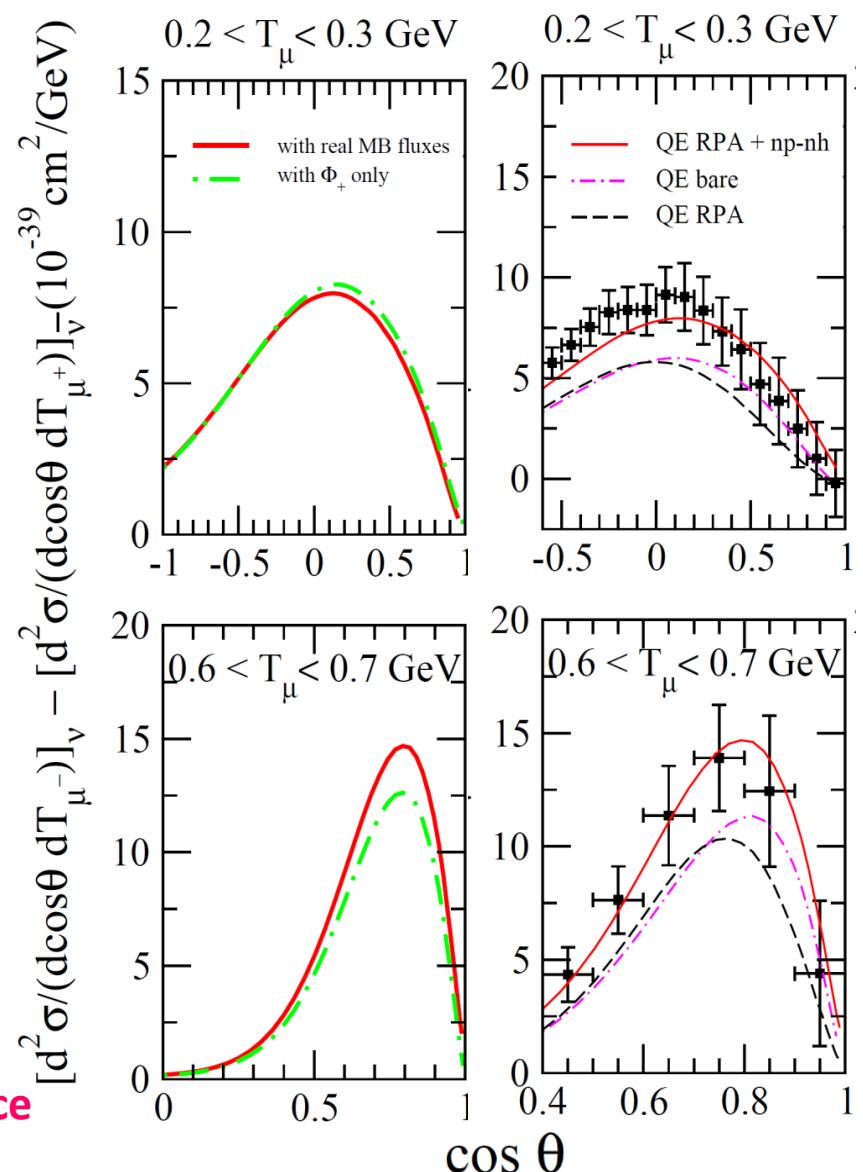


The VA interference term is experimentally accessible in MiniBooNE data



Need for the multinucleon component in the VA interference

It would be interesting to repeat similar analysis with other ν and antiv beams (T2K, NuMI)



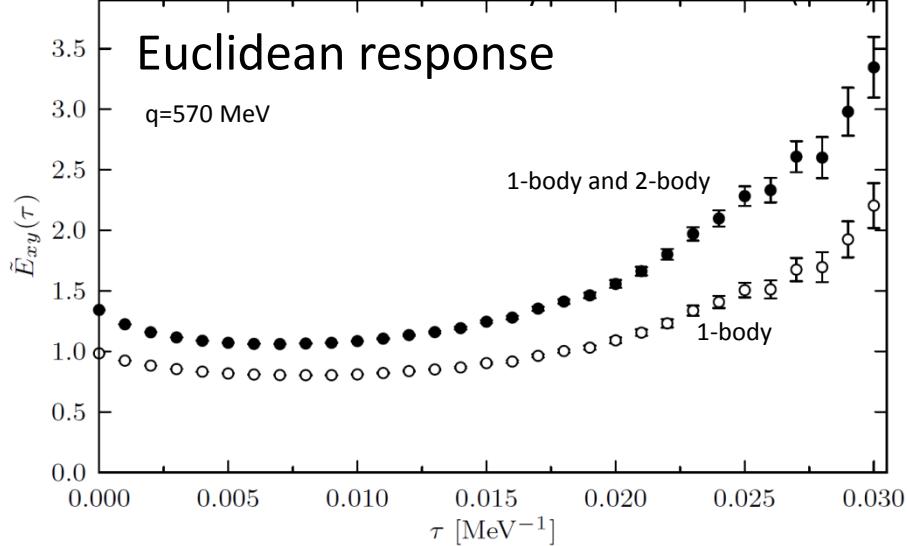
The VA interference term in an *ab-initio* microscopic approach

A. Lovato, S. Gandolfi, J. Carlson, S. C. Pieper, R. Schiavilla

Neutral weak current two-body contributions to sum rules and Euclidean responses in ^{12}C

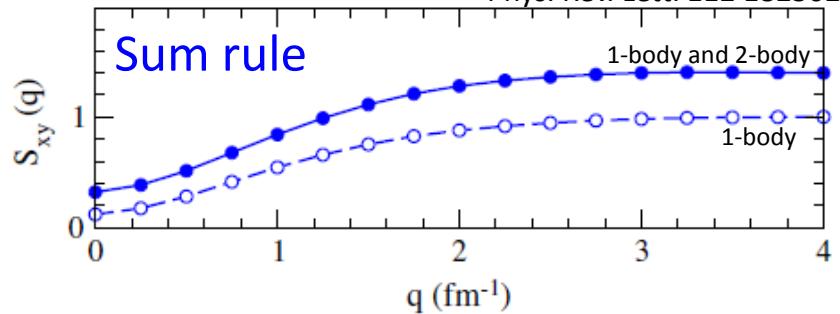
$$E_{\alpha\beta}(q, \tau) = C_{\alpha\beta}(q) \int_{\omega_{\text{th}}}^{\infty} d\omega e^{-\tau\omega} R_{\alpha\beta}(q, \omega)$$

Phys. Rev. C 91 062501 (2015)



$$S_{\alpha\beta}(q) = C_{\alpha\beta} \int_{\omega_{\text{el}}}^{\infty} d\omega R_{\alpha\beta}(q, \omega)$$

Phys. Rev. Lett. 112 182502 (2014)



important 2p-2h contributions
in the VA interference term

Some comments on this theoretical approach

Advantages:

- Include full realistic interactions fit to NN data with simultaneous two-body currents
- State of the art description of nuclear ground state and correlations

Disadvantages:

- Non relativistic currents
- No pion or Δ production
- Computing very demanding

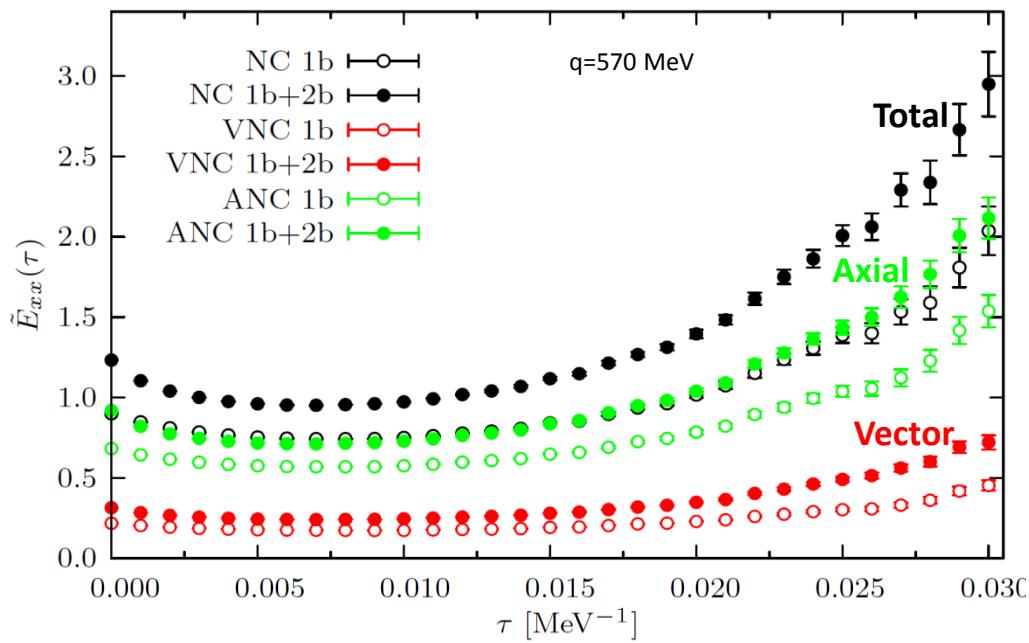
Limitation: an evaluation of ^{12}C responses and ν cross sections is beyond the present computational capabilities.

But the results obtained with this approach offer a benchmark for phenomenological methods

An instructive comparison of two different quantities

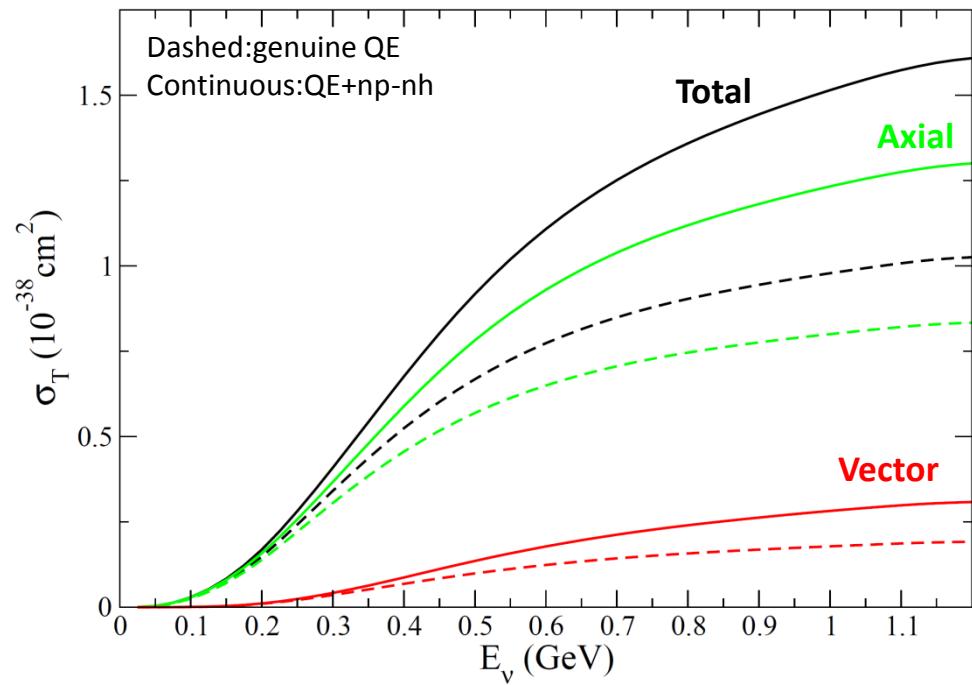
Euclidean NC transverse response

Lovato et al. Phys.Rev. C 91 062501 (2015)



Transverse contribution to the NC cross section

Martini et al.



In both approaches, similar behavior:

2p-2h important also in the Axial part of the transverse contribution

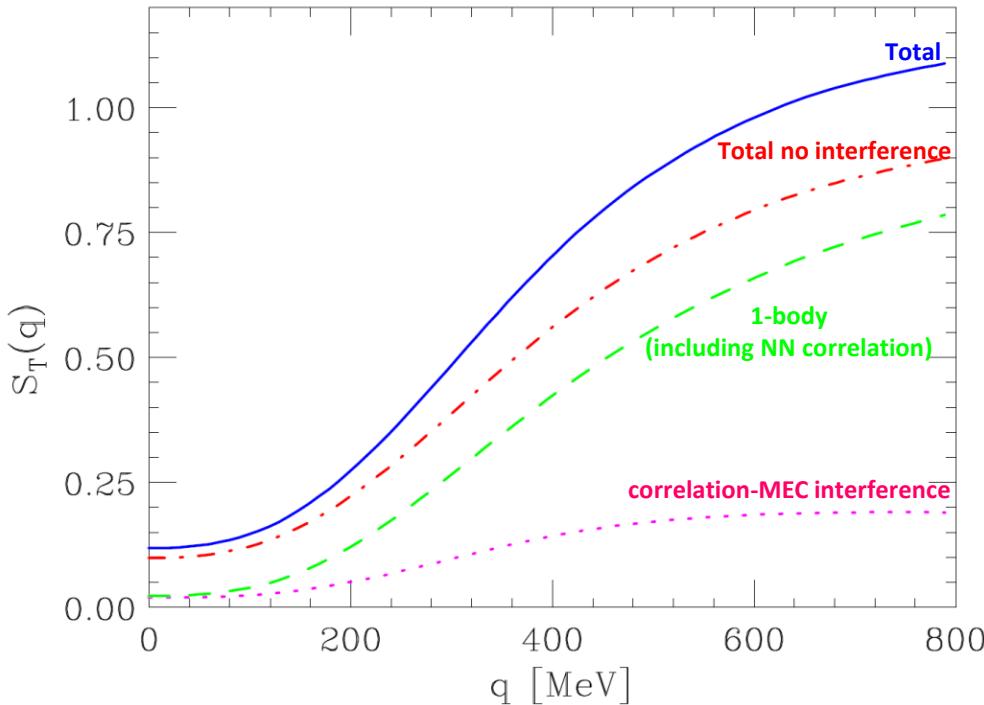
$$\frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = \sigma_0 [L_{00}R_{00} + L_{0z}R_{0z} + L_{zz}R_{zz} + L_{xx}R_{xx} \pm L_{xy}R_{xy}]$$

$\overset{\text{R}_V + \text{R}_A}{\uparrow}$

Another comparison of two different quantities

Sum rule of the transverse response

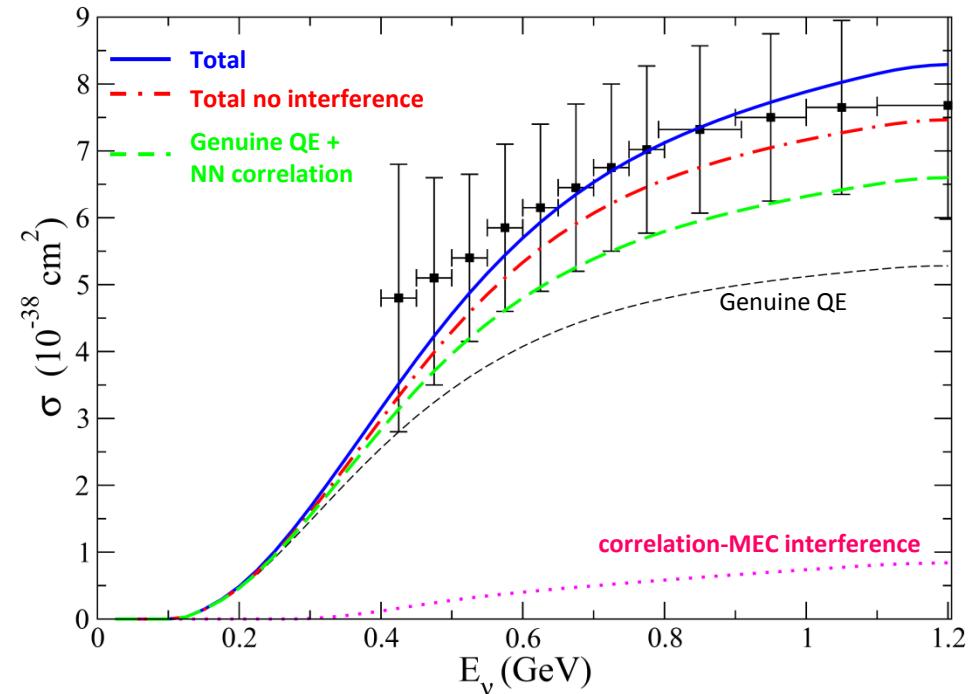
Benhar, Lovato, Rocco, Phys. Rev. C 92 024602 (2015)



- Sum rule function of q
- Only Vector Transverse

Neutrino CCQE-like cross section

Martini et al.



- Cross section function of E_v
- Total

Important contribution of NN correlation-MEC interference

P.S.

In the approach of Lovato et al., who work in a correlated basis, the effects of NN correlations are included in the 1 body contribution. For this reason Lovato et al. refer to the “NN correlation – MEC interference” as “one nucleon – two nucleon currents interference”

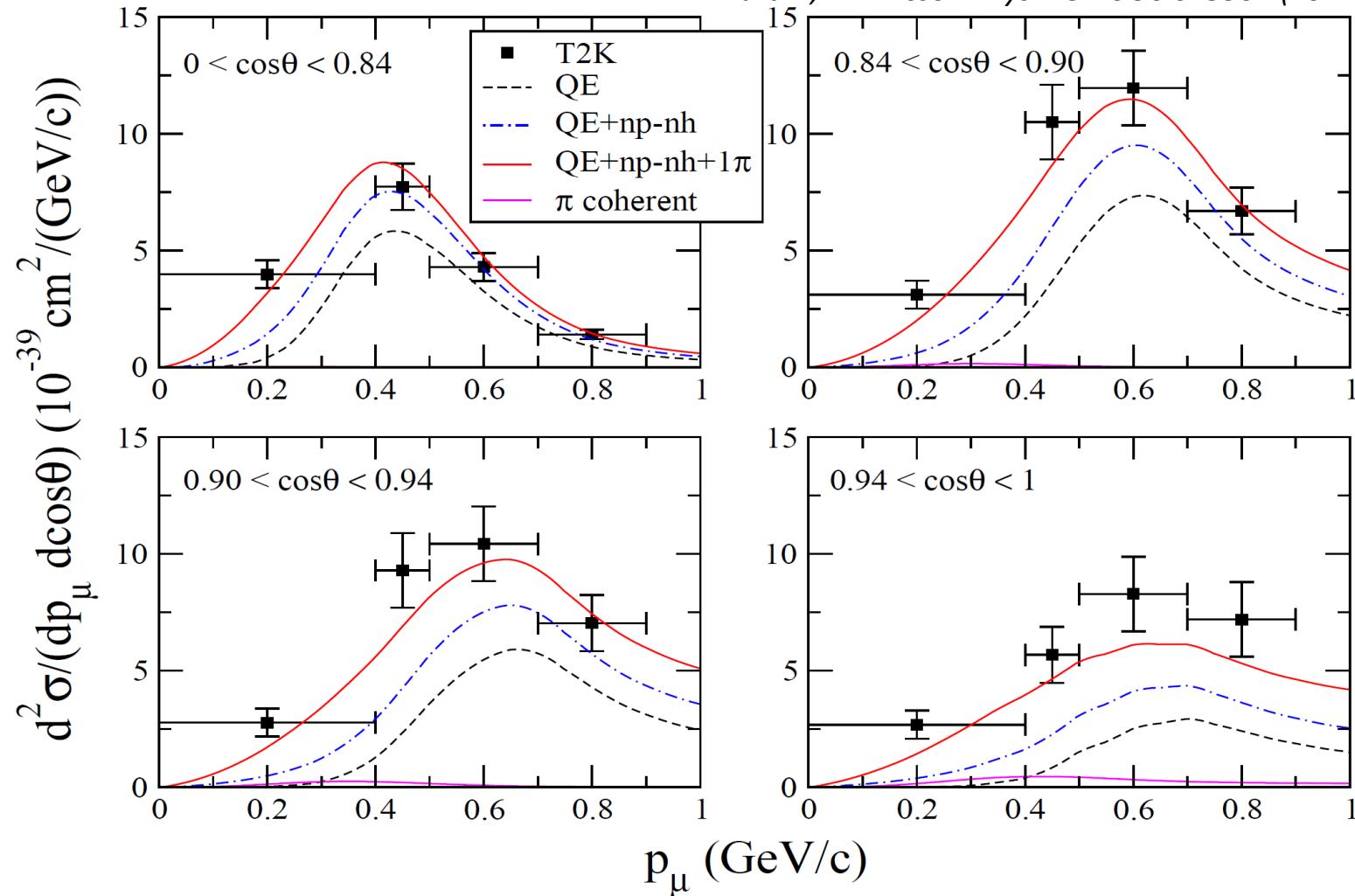
T2K CC inclusive (and CC0 π)

ν_μ T2K flux-integrated inclusive double differential cross section on carbon

The inclusive cross section is less affected by background subtraction with respect to exclusive ones

T2K Inclusive: *Phys. Rev. D* 87, 092003 (2013)

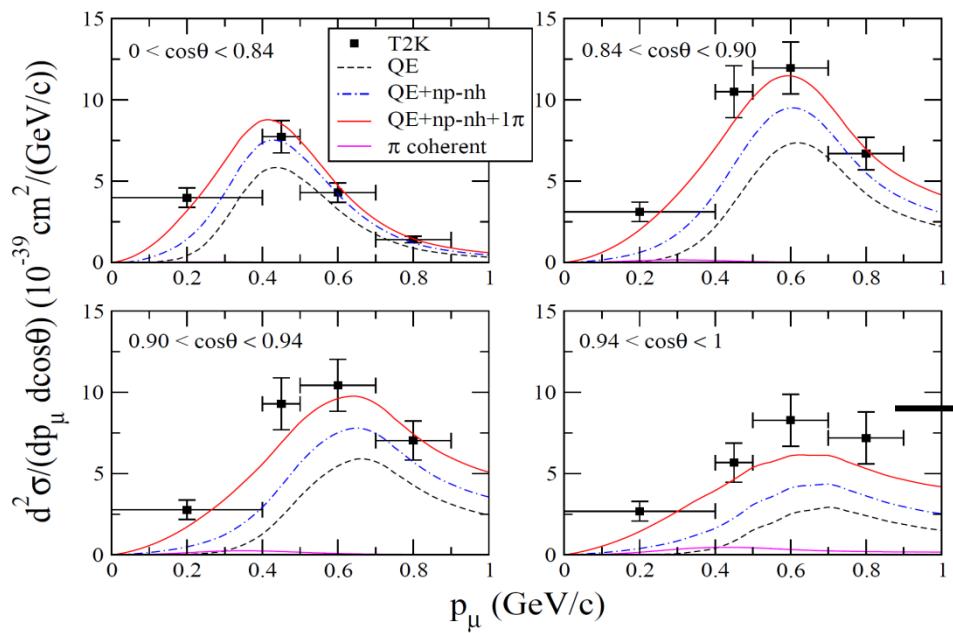
M. Martini, M. Ericson *Phys. Rev. C* 90 025501 (2014)



Test of the necessity of the multinucleon emission channel in an experiment with another neutrino flux with respect to the one of MiniBooNE.

ν_μ T2K flux-integrated inclusive double differential cross section on carbon

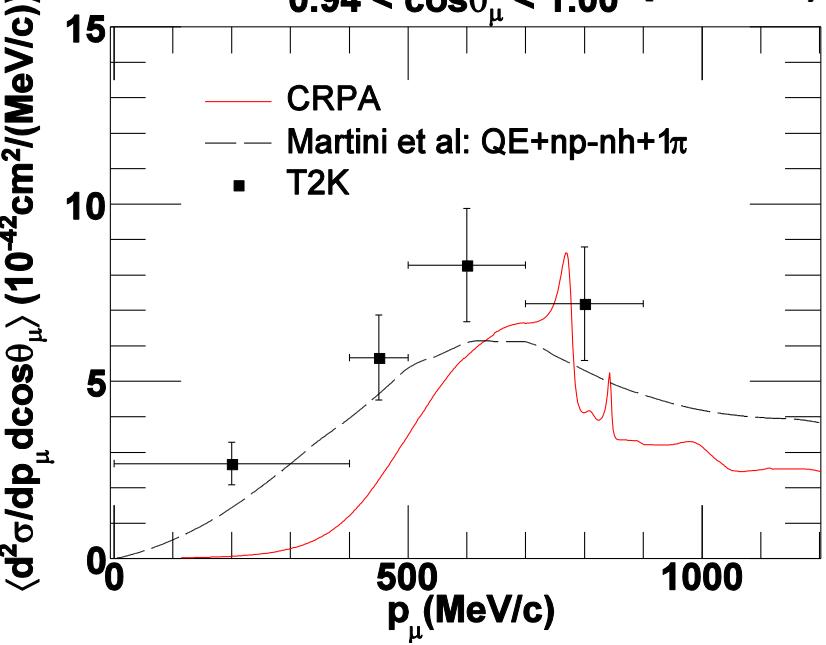
M. Martini, M. Ericson Phys. Rev. C 90 025501 (2014)



Even with the inclusion of the np-nh excitations, some undervaluation of the T2K data seems to show up in the **forward direction**.
It could be due to some contributions not included in this approach, such as excitations of **low-lying giant resonances**.

V. Pandey, N. Jachowicz et al. (Ghent) to be submitted

$0.94 < \cos\theta_\mu < 1.00$ [T. Van Cuyck talk]



**Impact of low-lying giant resonances
in the forward direction**

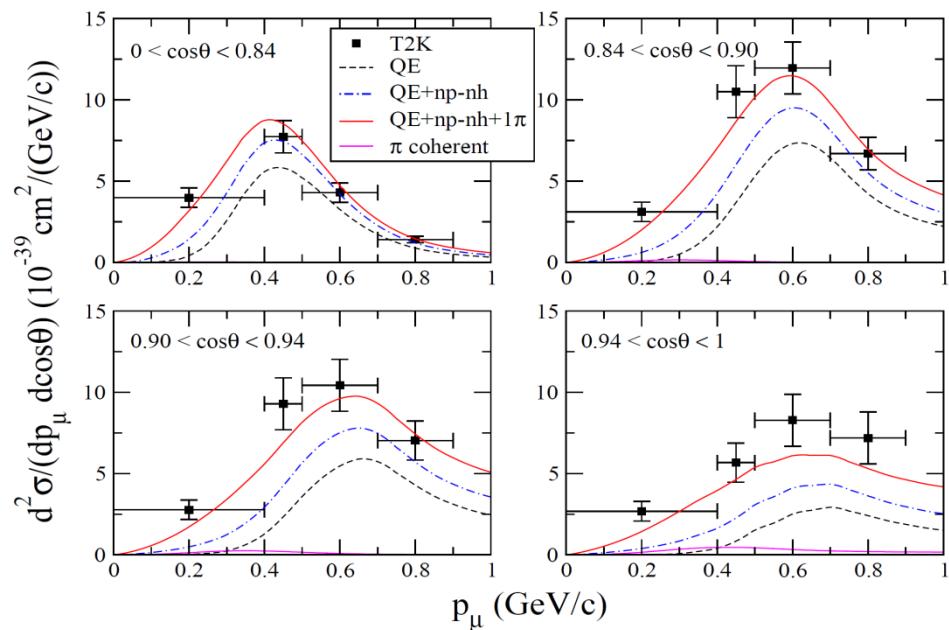
[See also V. Pandey et al., Phys. Rev. C 92, 024606 (2015)]

[Low-energy excitations contributions: **A. Samana and T. Van Cuyck talks**]

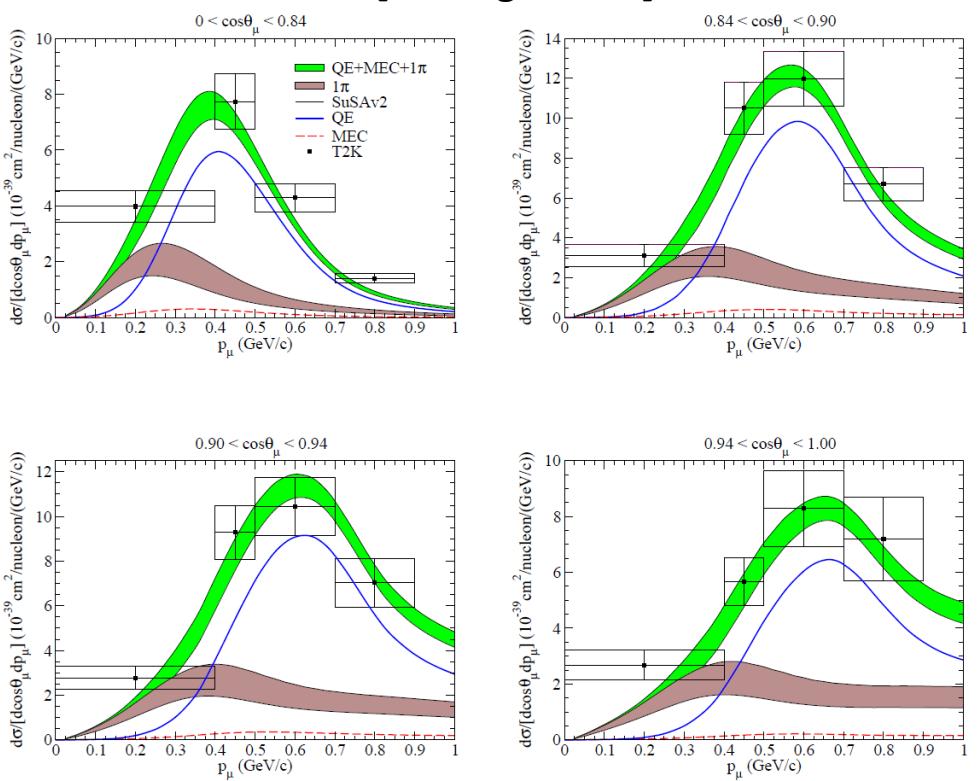
ν_μ T2K flux-integrated inclusive double differential cross section on carbon

Ivanov, Megias et al. arXiv 1506.00801 (2015)

M. Martini, M. Ericson Phys. Rev. C 90 025501 (2014)



[G. Megias talk]



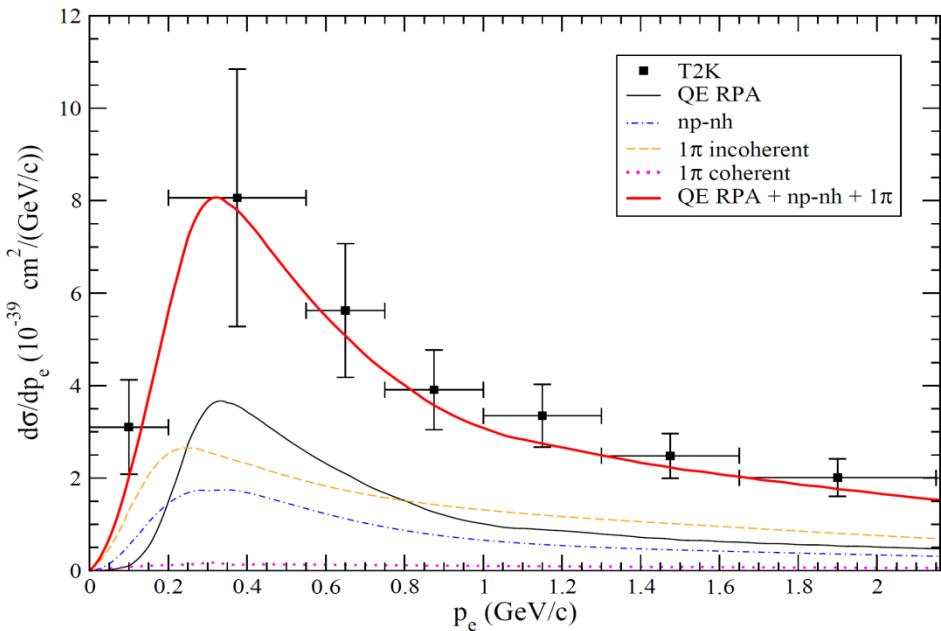
Agreement with data

With respect to Martini and Ericson:
larger genuine QE (no RPA quenching) and lower np-nh contributions (only MEC and only in the vector sector)

ν_e T2K flux-integrated inclusive differential cross section on carbon

T2K: PRL 113, 241803 (2014)

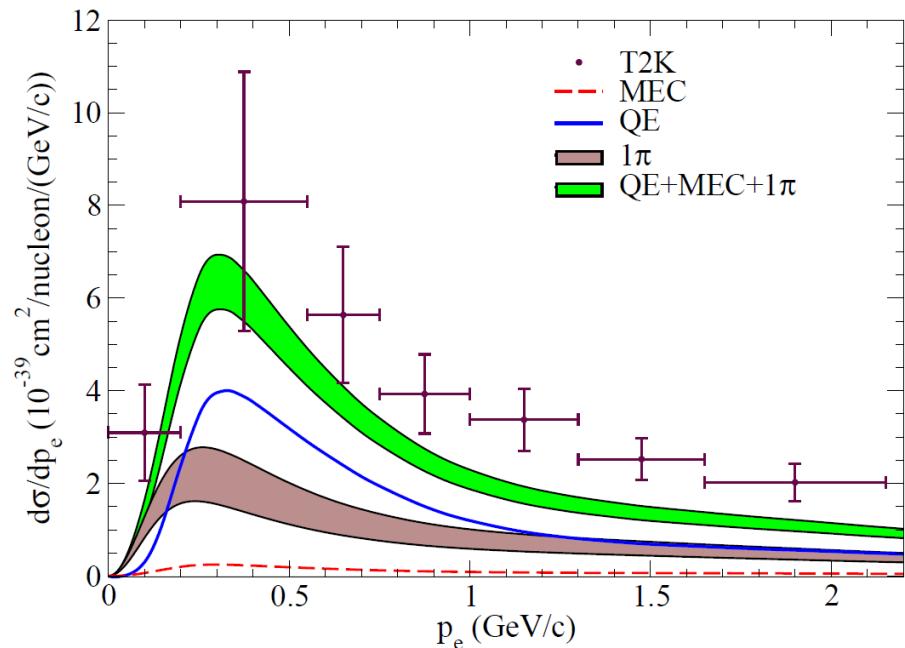
Martini et al., to be submitted



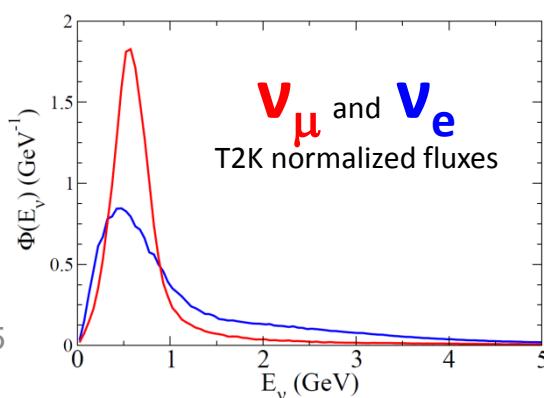
- Agreement with data (small tendency to underestimate)
- Important presence of np-nh which even dominates the genuine QE for small p_e

[G. Megias talk]

Ivanov, Megias et al. arXiv 1506.00801 (2015)



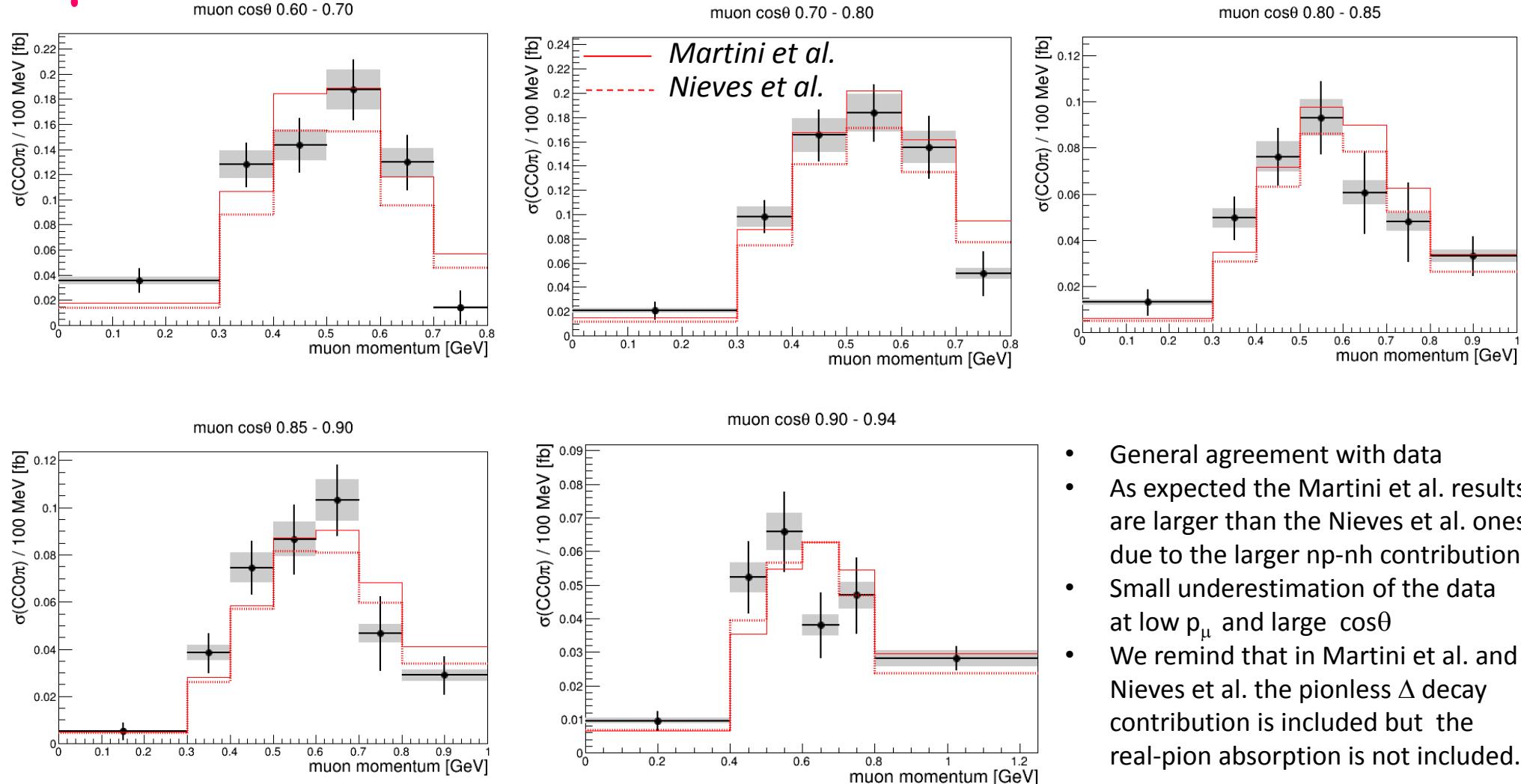
- Underestimation of the data
- Small np-nh contribution (only vector, only MEC)



- Important tail in the electronic neutrino flux
- In the ν_e case other reaction mechanisms such as multi-meson production and DIS expected to be most important with respect to the ν_μ case

T2K flux-integrated CC0 π measurement vs CCQE+np-nh calculations

[S. Bolognesi and A. Furmanski talks]



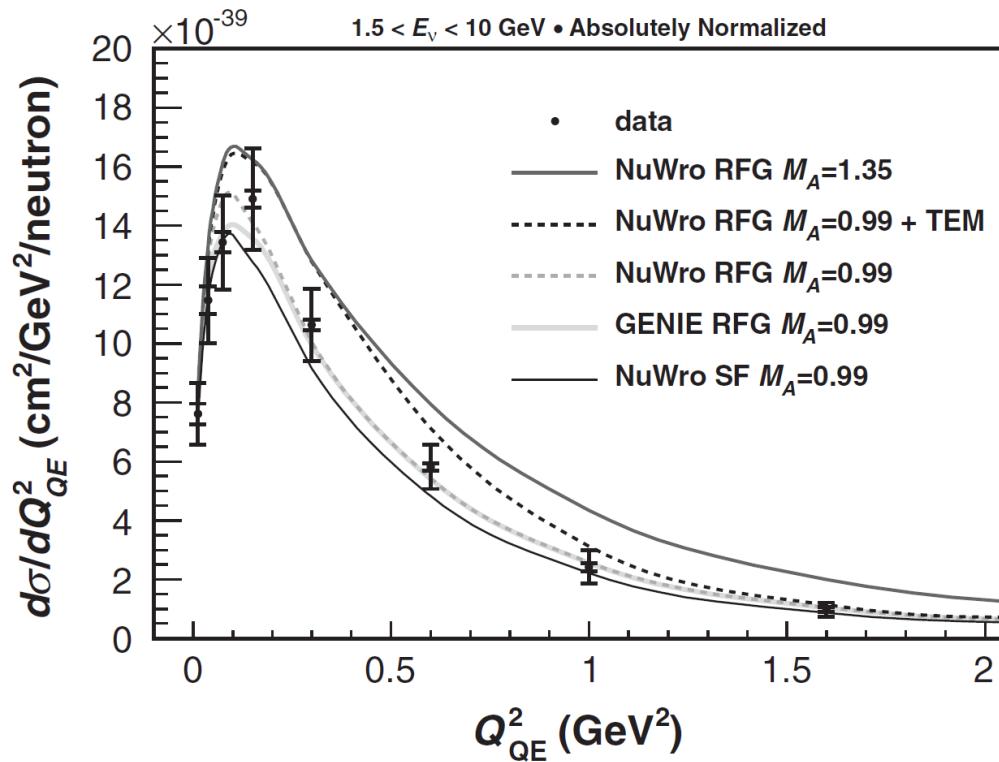
- General agreement with data
- As expected the Martini et al. results are larger than the Nieves et al. ones due to the larger np-nh contribution
- Small underestimation of the data at low p_μ and large $\cos\theta$
- We remind that in Martini et al. and Nieves et al. the pionless Δ decay contribution is included but the real-pion absorption is not included.

MINER ν A CCQE

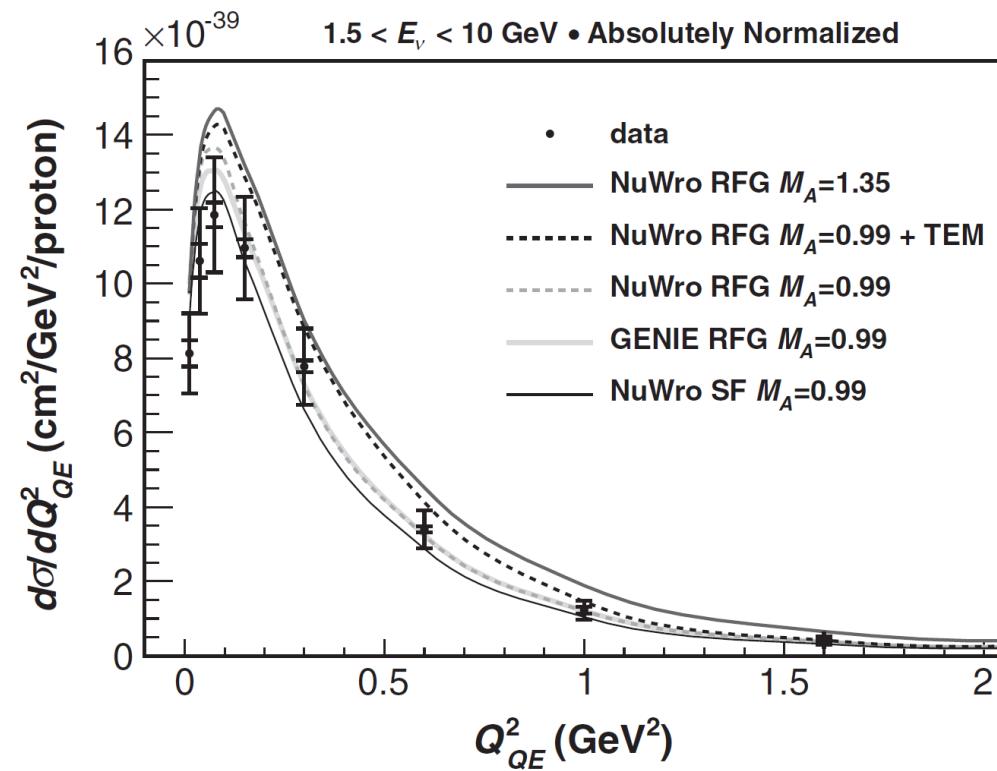
MINERvA ($E_\nu \sim 3.5$ GeV) CCQE Q^2 distribution

V

\overline{V}



PRL 111 022502 (2013)



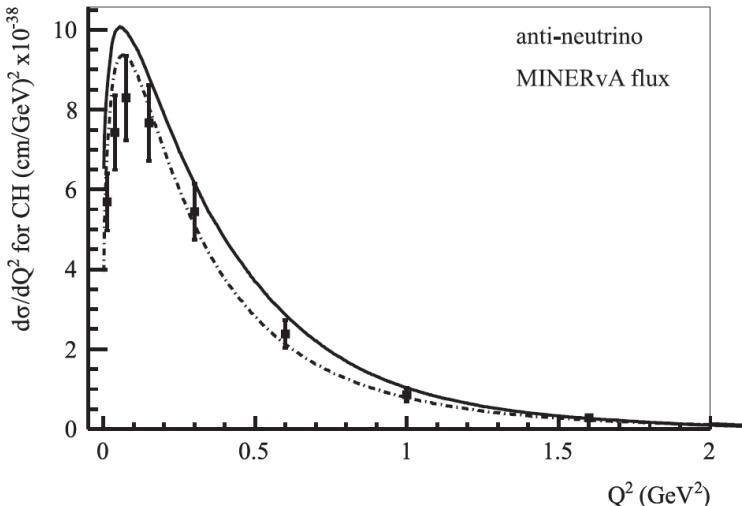
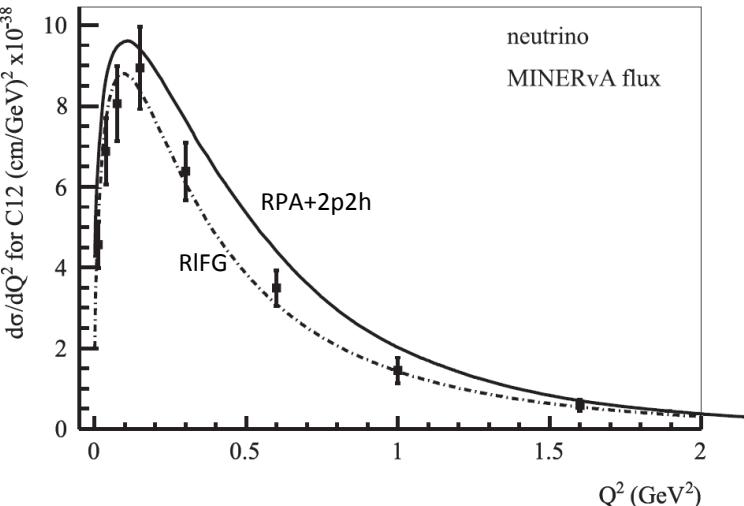
PRL 111 022501 (2013)

V

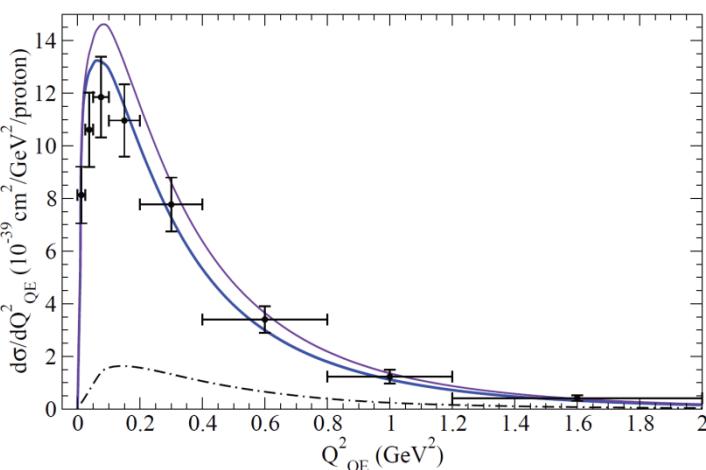
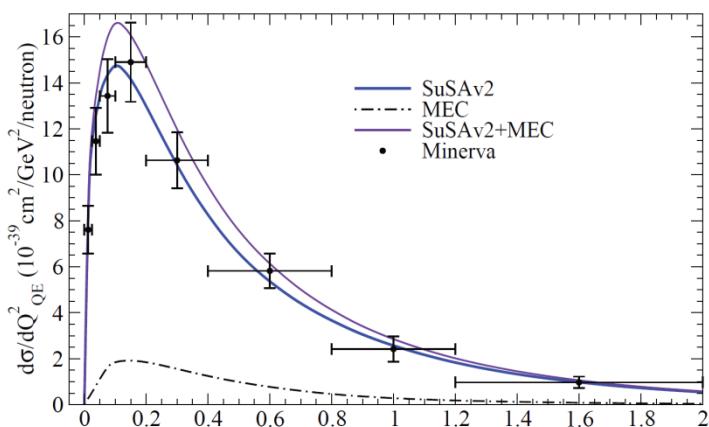
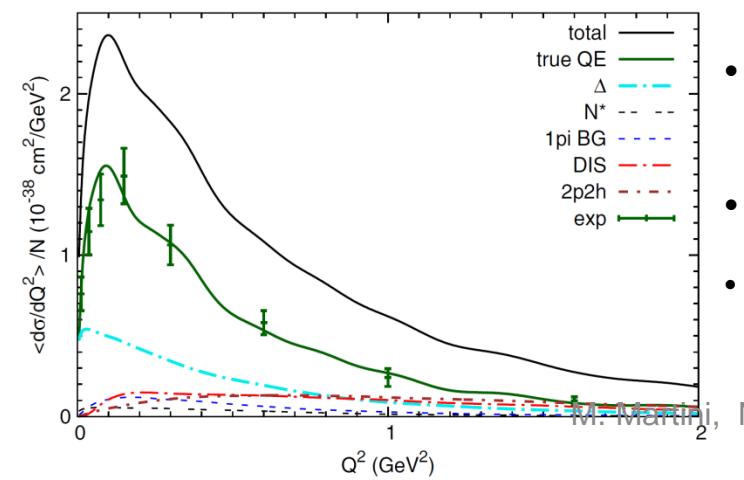
Gran, Nieves

et al.

PRD 88 (2013)

Megias, Amaro
et al.

PRD 91 (2015)

Mosel et al.
PRD 89 (2014)

10/8/2015

M. Martin, NuFact15

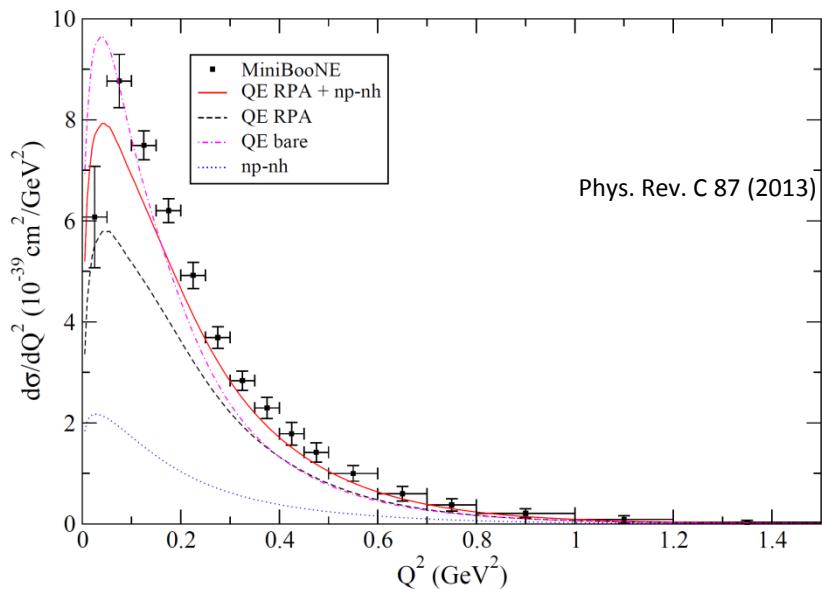
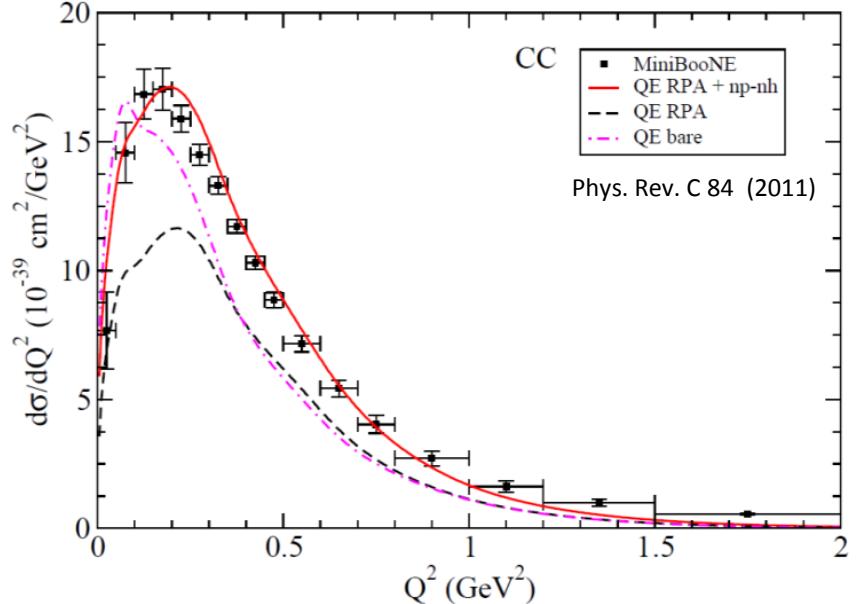
- **MINERvA CCQE Q^2 distributions can be reproduced also without the inclusion of np-nh**
- **This is not the case of the MiniBooNE Q^2 distributions**
- Mosel et al: “The sensitivity to details of the treatment of np-nh contributions is smaller than the uncertainties introduced by the Q^2 reconstruction and our insufficient knowledge of pion production”

Coming back to MiniBooNE CCQE: the Q^2 distributions

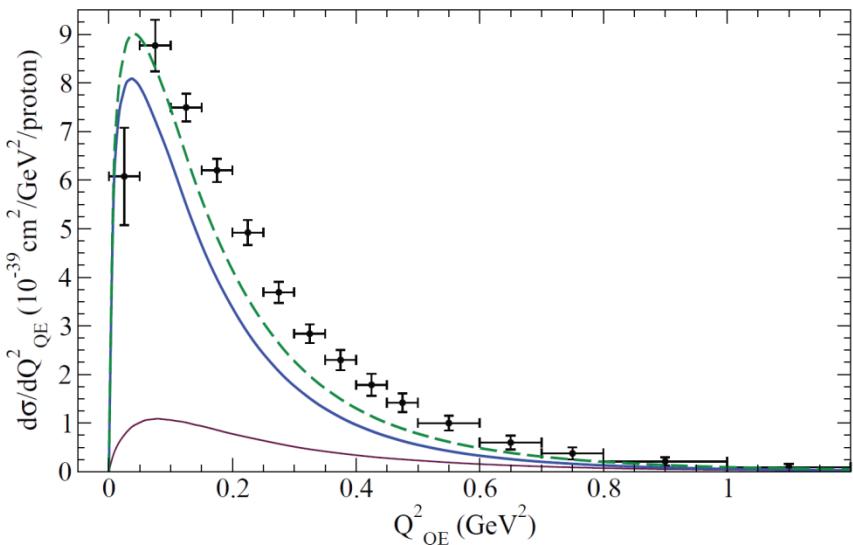
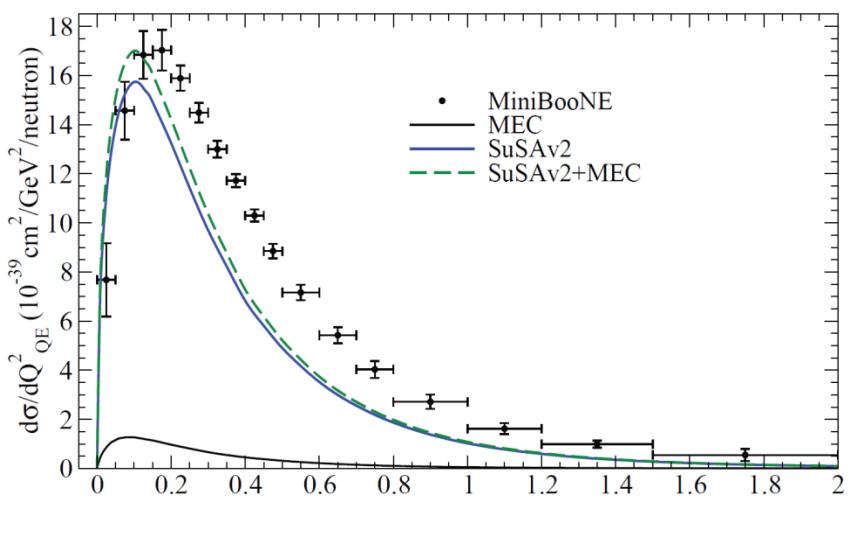
V

V

Martini
et al.



Megias,
Amaro
et al.
PRD 91
(2015)

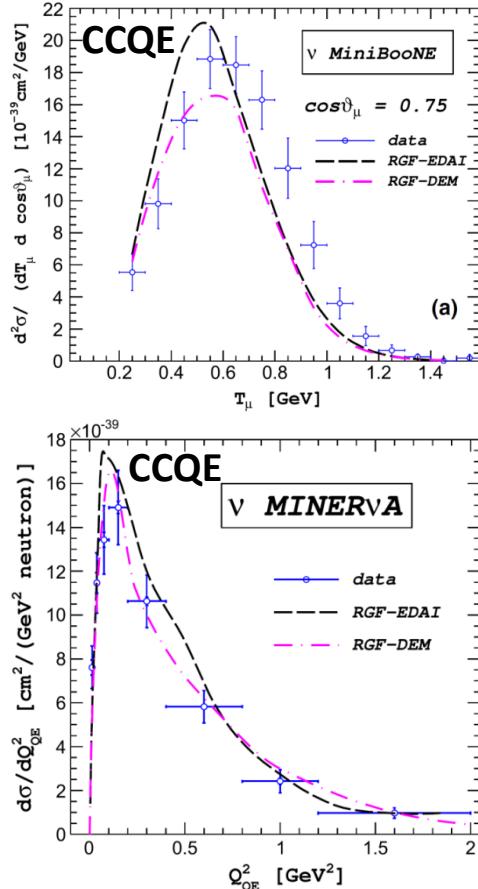


p.s. the additional normalization uncertainty in the MiniBooNE data of 10% for neutrinos and of 17.2% for antineutrinos is not shown here

The relativistic Green's function (RGF) model with a complex Optical Potential

- The results are obtained retaining only the one-body part of the nuclear current.
- The model can include not only direct 1-nucleon emission processes but also multinucleon and Δ excitations due to the nucleon FSI
- The use of a phenomenological Optical Potential does not allow to disentangle and evaluate the role of a specific reaction process.

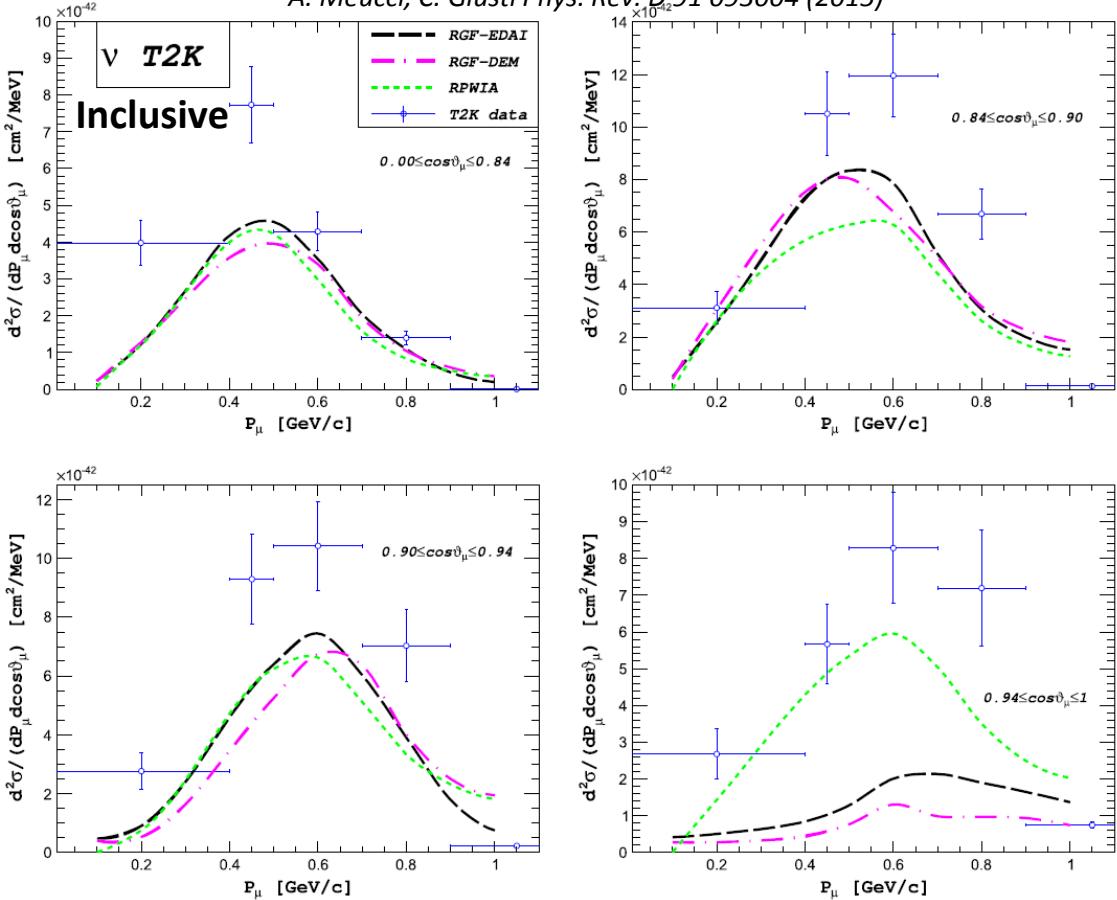
A. Meucci, C. Giusti Phys. Rev. D 89 117301 (2014)



Simultaneous reasonable agreement with
MiniBooNE and MINERvA CCQE

[C. Giusti talk]

A. Meucci, C. Giusti Phys. Rev. D 91 093004 (2015)



Indication of a minor contribution of the pion-production channel to the RGF cross sections or of large multinucleon and pion-production contributions to the experimental CC-inclusive cross sections.

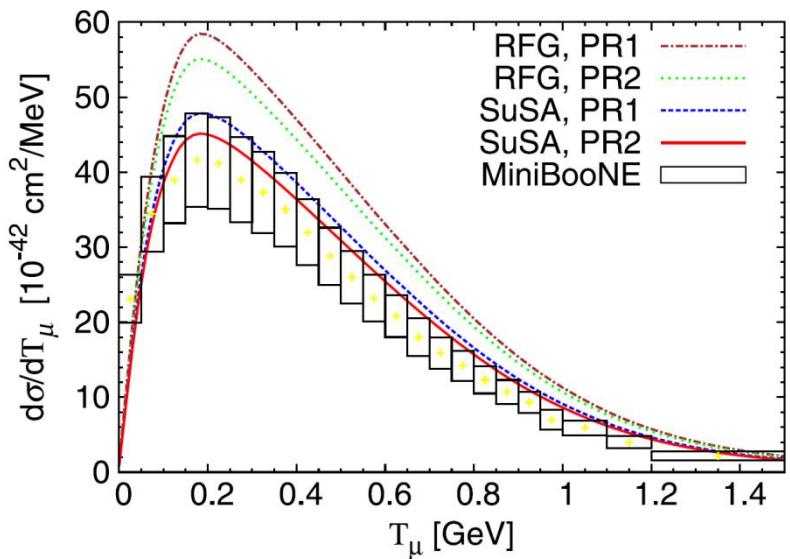
1π production

MiniBooNE flux-integrated CC1 π^+ differential cross section

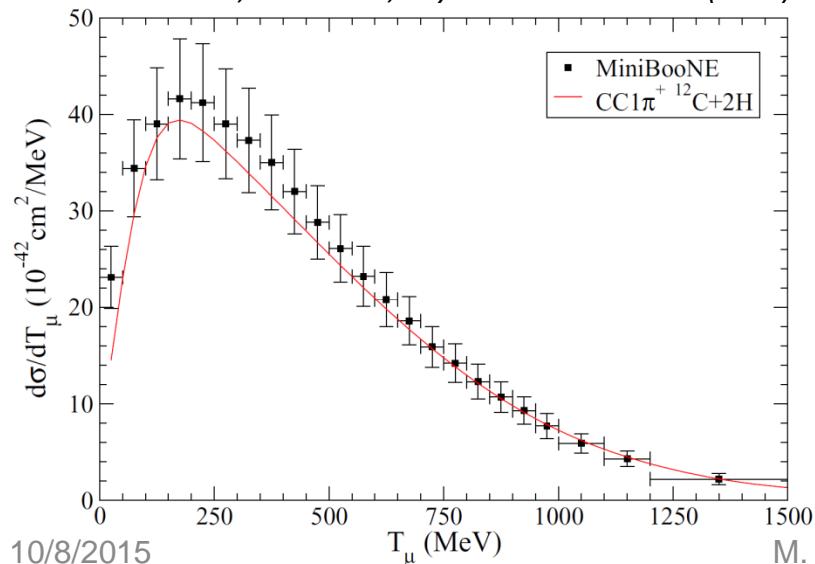
MiniBooNE Phys. Rev. D 83 052007 (2011)

function of T_μ

Ivanov et al. Phys. Lett. B 711 (2012) 178-183

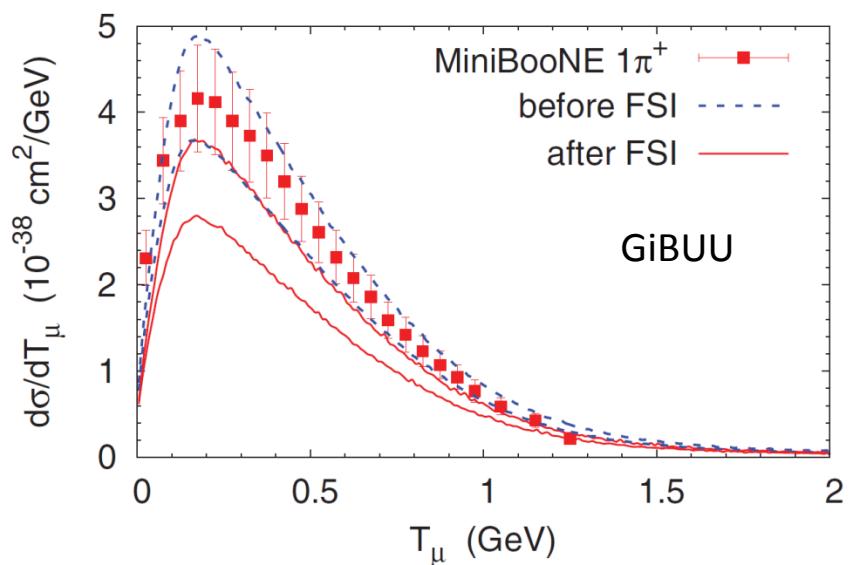


M. Martini, M. Ericson, Phys. Rev. C 90 025501 (2014)



M. Martini, NuFact15

Lalakulich, Mosel , Phys.Rev. C 87 (2013) 014602

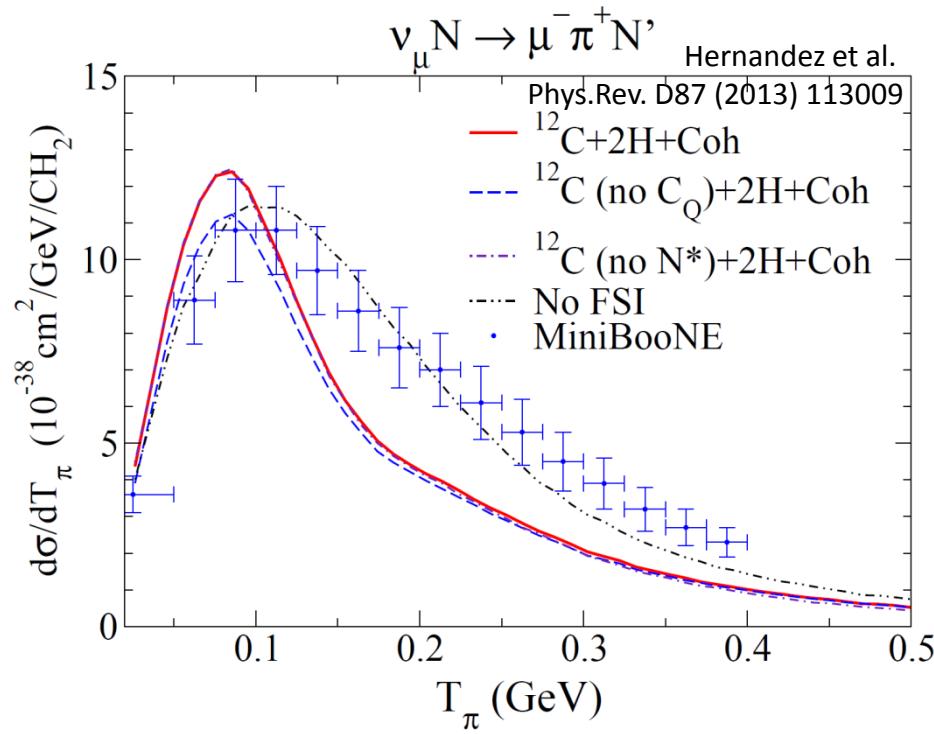


General agreement between
theoretical calculations and data

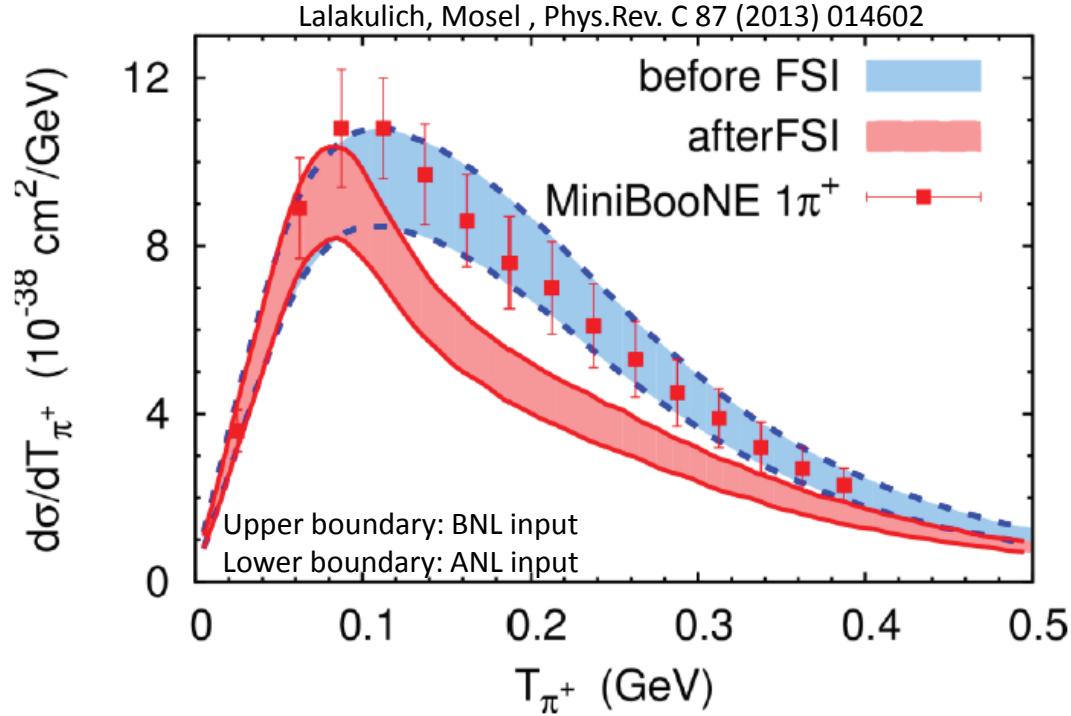
MiniBooNE flux-integrated CC1 π^+ differential cross section

MiniBooNE Phys. Rev. D 83 052007 (2011)

function of T_π



Valencia



GiBUU

controversy

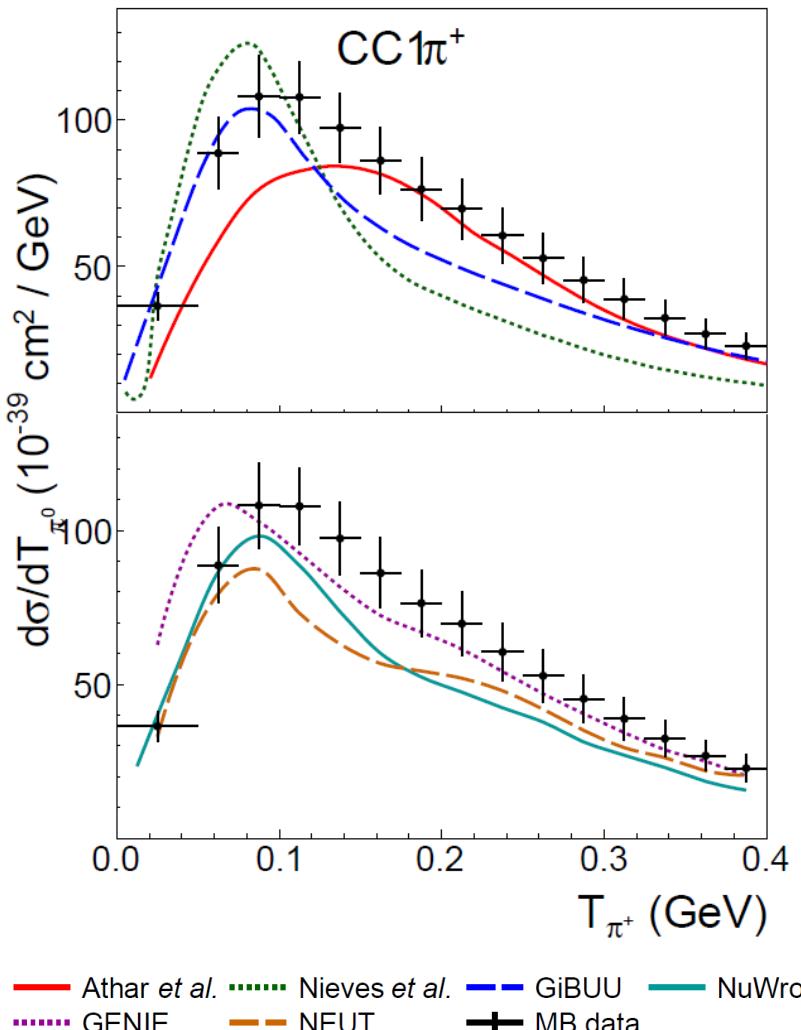
- Theories (with Δ medium effects and pion rescattering) do not agree with pion KE spectrum

[Meson production in resonance region: S. Nakamura talk]

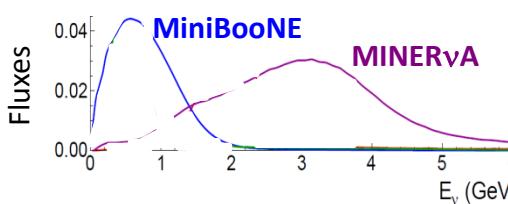
MiniBooNE vs MINERvA CC1 π^+ production

MiniBooNE

Rodrigues, arXiv:1402.4709

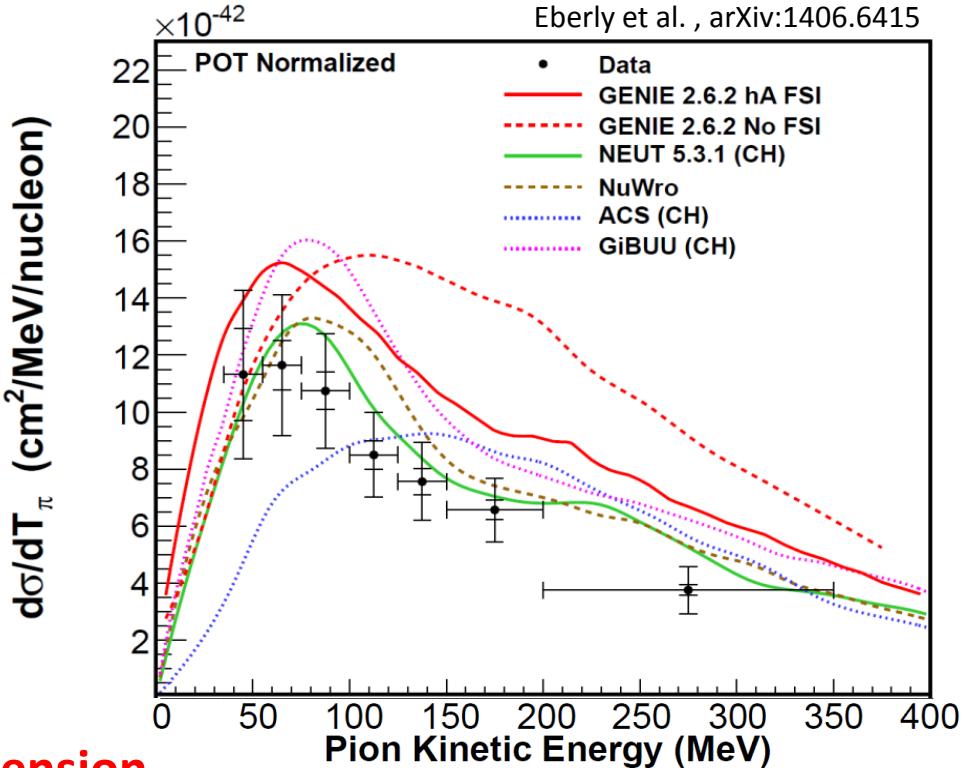


10/8/2015



MINERvA

Eberly et al. , arXiv:1406.6415



Some tension

Recent theoretical investigations:

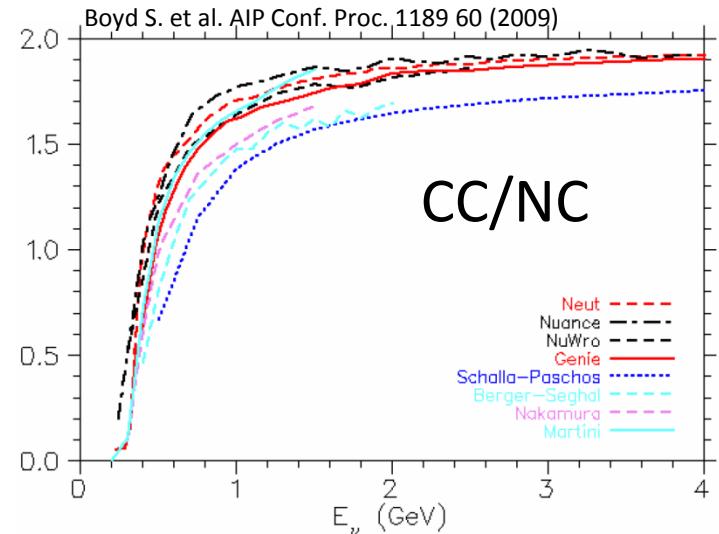
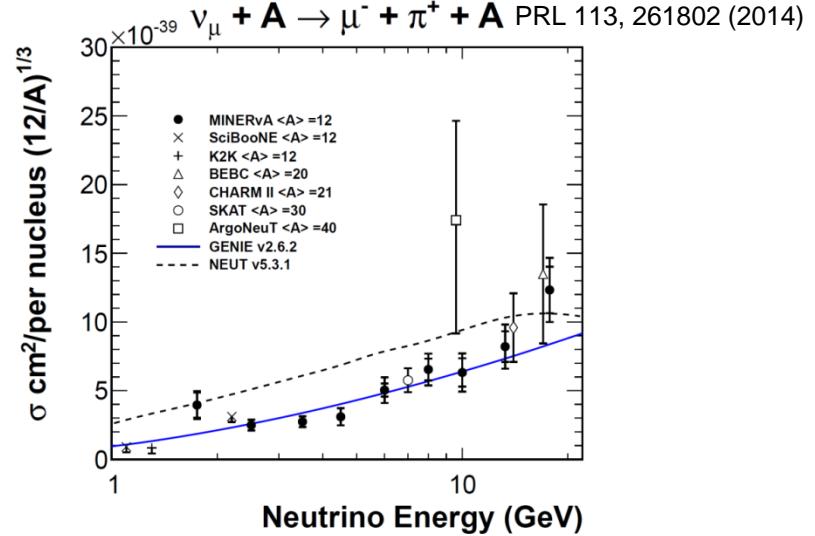
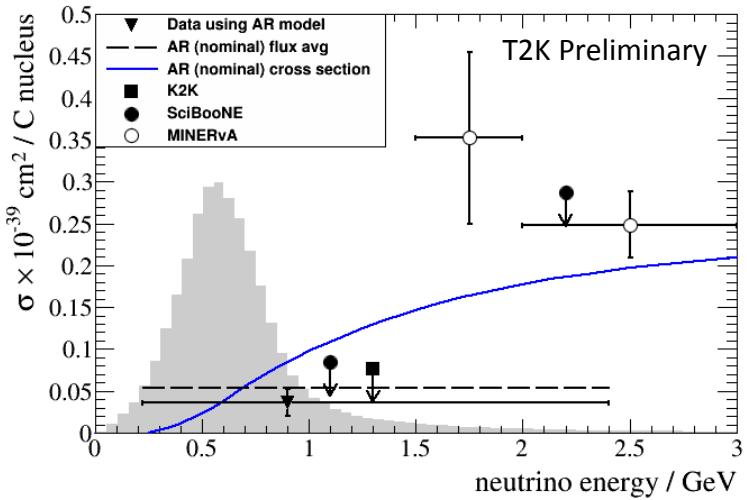
- J. T. Sobczyk and J. Źmuda, Phys. Rev. C 91, 045501 (2015)
- U. Mosel, Phys. Rev. C 91, 065501 (2015)
- J. Y. Yu et al. Phys. Rev. D 91, 054038 (2015).

Coherent π production

K2K and SciBooNE: only upper limits for coherent π^+ production at neutrino energies $\sim 1\text{ GeV}$

Recently MINERvA and ArgoNeut see evidence for CC coherent pion production

T2K preliminary results: $\sim 2.5 \sigma$ indication of coherent π^+ production at neutrino energies $\sim 1\text{ GeV}$



Coherent puzzle at $E_\nu \sim 1 \text{ GeV}$

Theoretical models:

$$\frac{\pi^+ \text{ coh. CC}}{\pi^0 \text{ coh. NC}} = 1.5 \sim 2$$

SciBooNE:

$$\frac{\pi^+ \text{ coh. CC}}{\pi^0 \text{ coh. NC}} = 0.14^{+0.30}_{-0.28}$$

Kurimoto et al, PRD 81 (2010)

Recent developments in neutrino-nucleus scattering theory

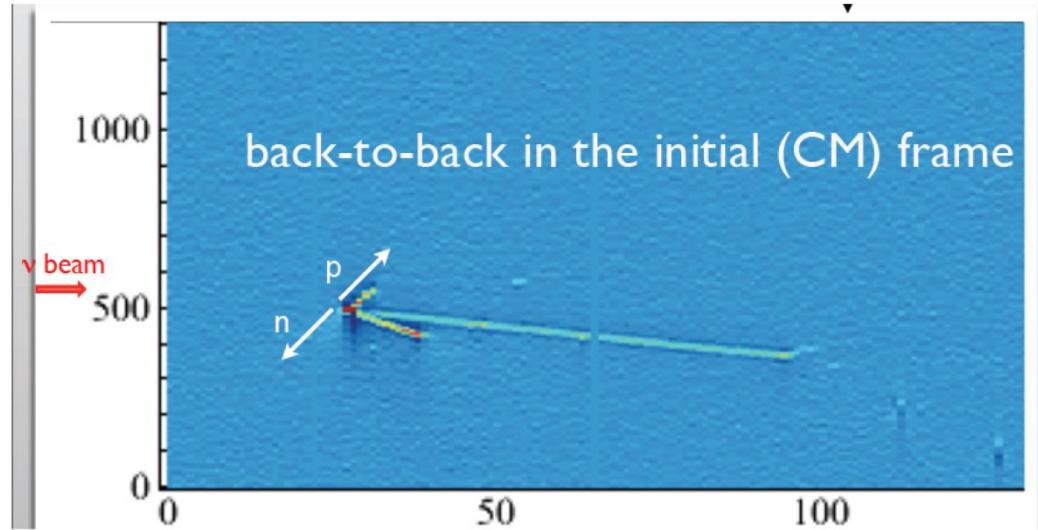
Summary

- Several theoretical calculations agree on the crucial role of the multinucleon channel (not contained in the generators) to explain MiniBooNE CCQE-like data \Rightarrow Solution of M_A puzzle
- Neutrino energy reconstruction and neutrino oscillation analysis are affected by np-nh
- There are some differences on the way to treat this np-nh channel which are reflected in the comparisons with the MiniBooNE neutrino and antineutrino data
- Nuclear effects generate an asymmetry between ν and anti ν interaction: important for the investigation of CP violation effects
- There are recent interesting T2K flux-integrated theoretical calculations compared with the ν_μ and ν_e CC inclusive and ν_μ CC0 π experimental results
- The role of np-nh in the comparisons between the theoretical calculations and the MINERvA results is less evident
- There are some controversies and puzzles in the one pion production channel: MiniBooNE vs theory ; MiniBooNE vs MINERvA vs theory; SciBooNE coherent pion

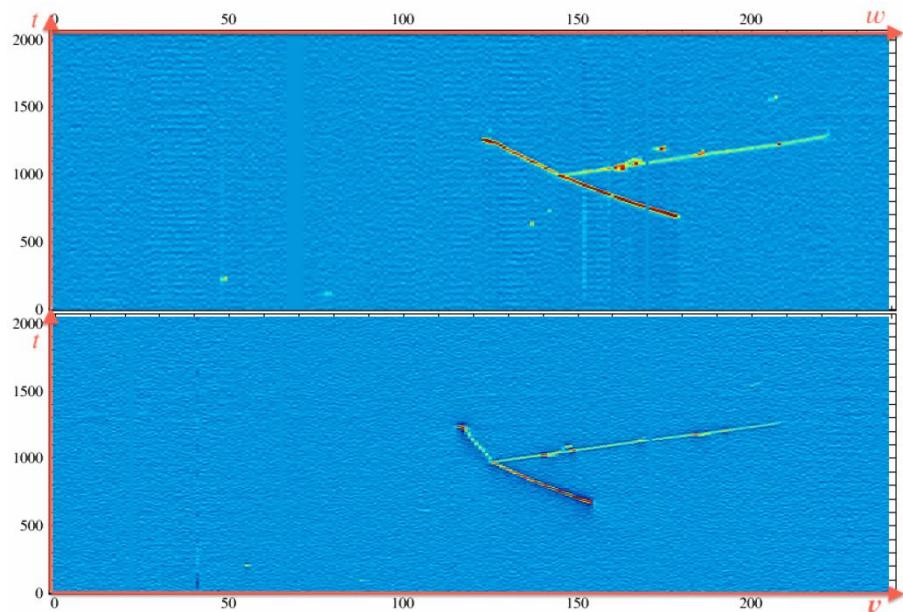
Spares

ArgoNeut

arXiv:1501.01983



Phys.Rev. D90 (2014) 1, 012008



Isospin content: correlated pairs and observables

Martini et al. PRC 80 065501 (2009)

“Also an experimental identification of the final state would be of a great importance to clarify this point. In particular the charge of the ejected nucleons will be quite significant. Because tensor correlations involve $n-p$ pairs, the ejected pair is predominantly $p-p$ ($n-n$) for charged current neutrino (antineutrino) reactions and $n-p$ for neutral current.”

Gran et al. PRD 88 11307 (2013)

“The mix of initial state for these 2p2h interactions has a complicated dependence, from 50% to 80% pn initial state for the non- Δ and Δ peaks, respectively”

Lovato et al. PRL 112 182502 (2014)

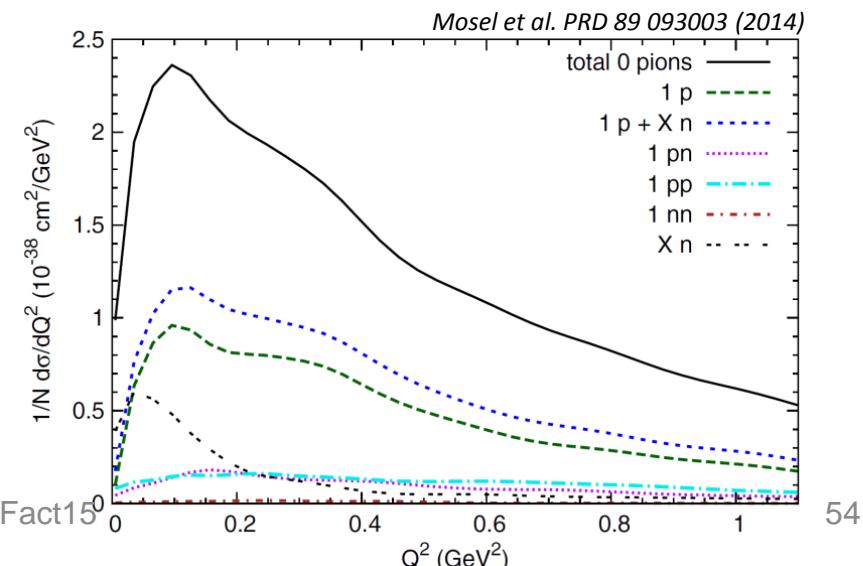
“The present study suggests that two nucleon currents generate a significant enhancement of the single-nucleon neutral weak current response, even at quasi-elastic kinematics. This enhancement is driven by strongly correlated np pairs in nuclei.”

MINERvA PRL 111 022501 (2013)

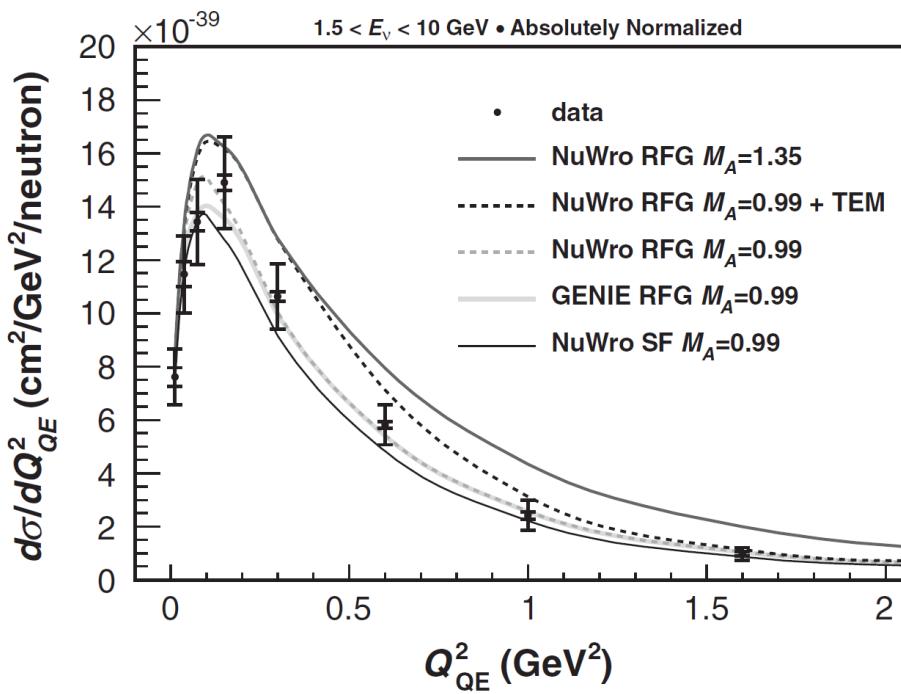
The MINERvA vertex energy on antineutrino mode “might be explained if the dominant multibody process is $\overline{\nu_\mu}(np) \rightarrow \mu^+ nn$ since MINERvA is not very sensitive to low energy neutrons. A similar analysis on neutrino mode data is consistent with additional protons in the final state”

Mosel et al. PRD 89 093003 (2014)

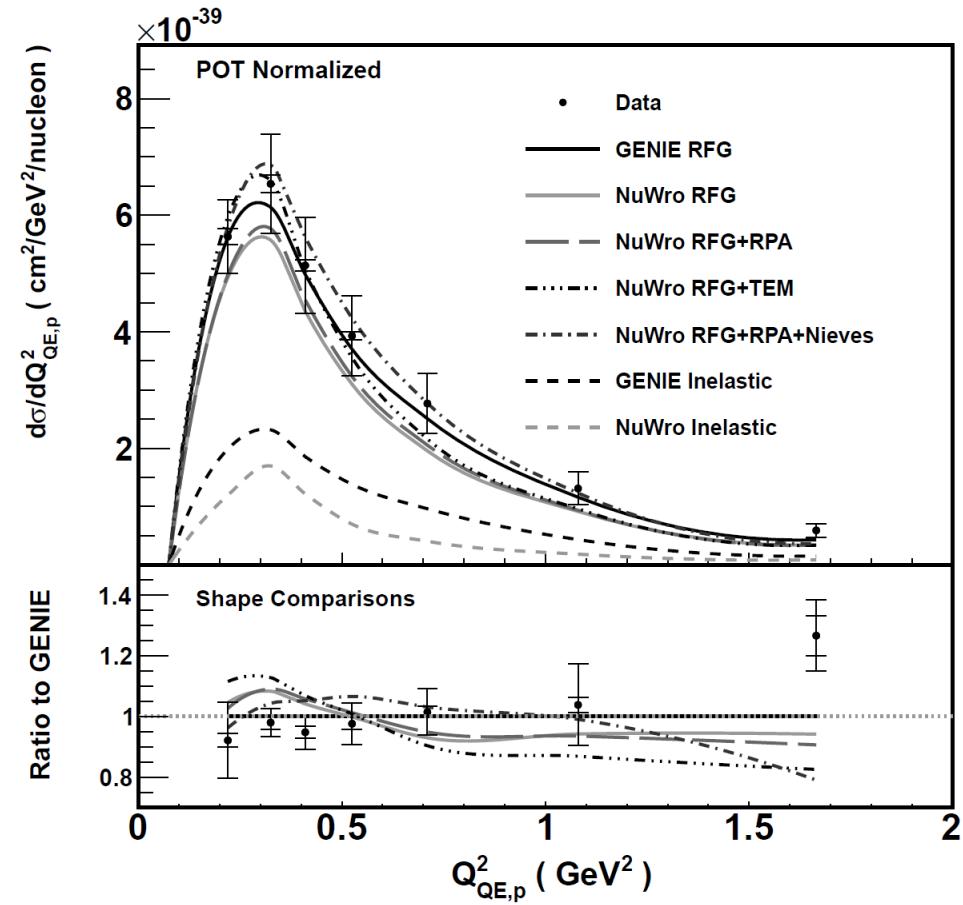
“The channels with a pp or a pn pair are very similar, quite flat, and suppressed and thus of minor importance. Interesting, however, is the pileup of strength seen in the Xn channel at small $Q^2 \approx 0.1 \text{ GeV}^2$. This is entirely due to fsi.”



MINERvA Q² distributions



PRL 111 022502 (2013)



Phys.Rev. D91 (2015) 7, 071301

MINERvA vs Spectral Function

ARTUR M. ANKOWSKI

PHYSICAL REVIEW D **92**, 013007 (2015)

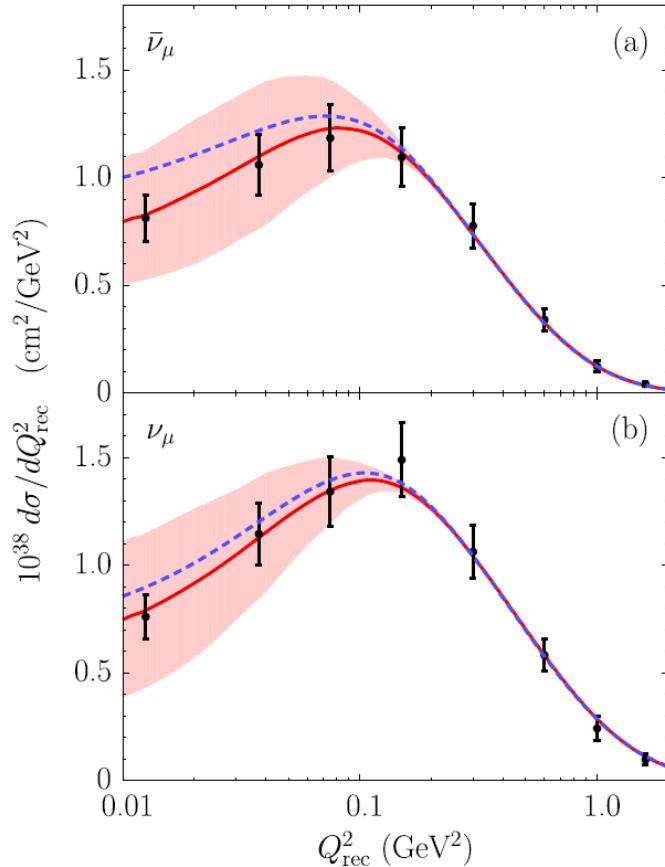
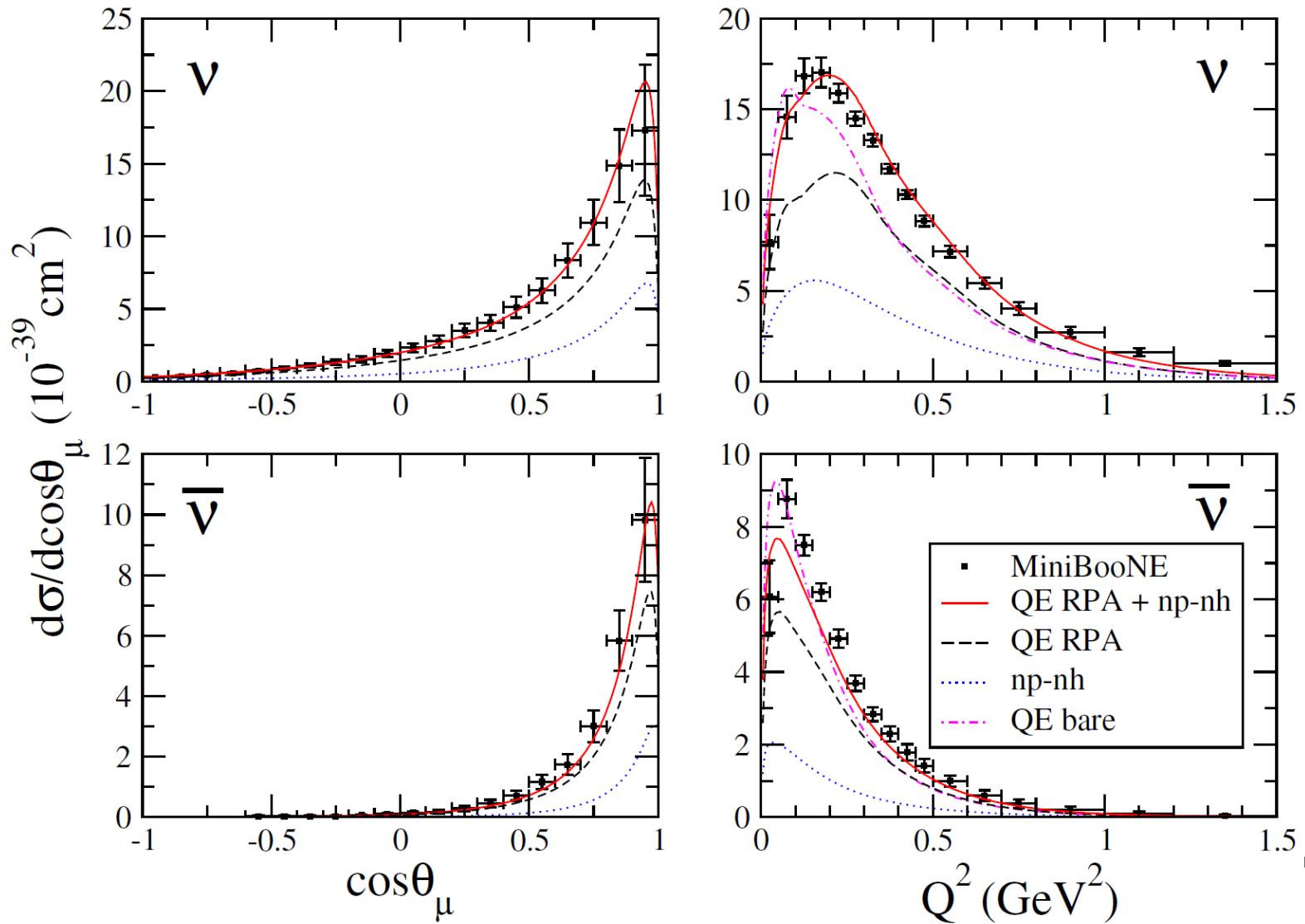


FIG. 2 (color online). Differential cross sections $d\sigma/dQ_{\text{rec}}^2$ for CC QE (a) $\bar{\nu}_\mu$ and (b) ν_μ scattering in MINERvA. The SF calculations without (dashed line) and with (solid lines) FSI effects [9] are compared to the data [1,2]. The bands represent theoretical uncertainties.

TABLE I. Fit results to the CC QE MINERvA data.

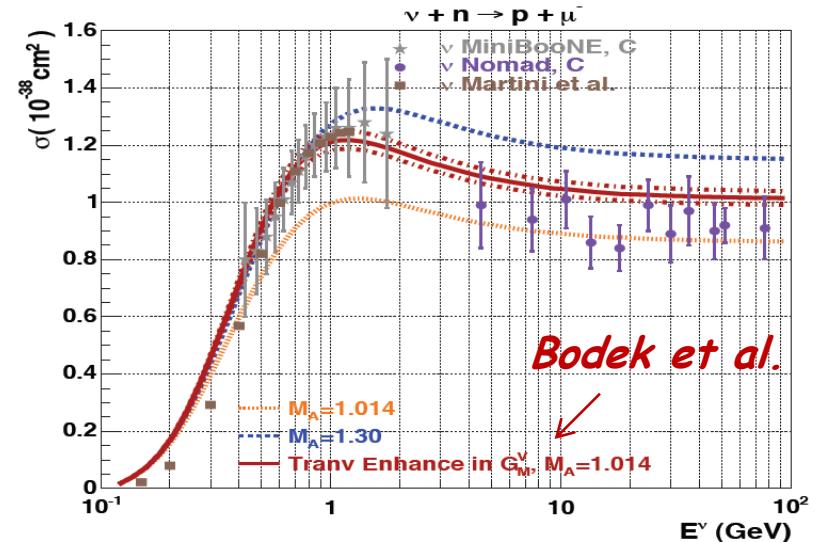
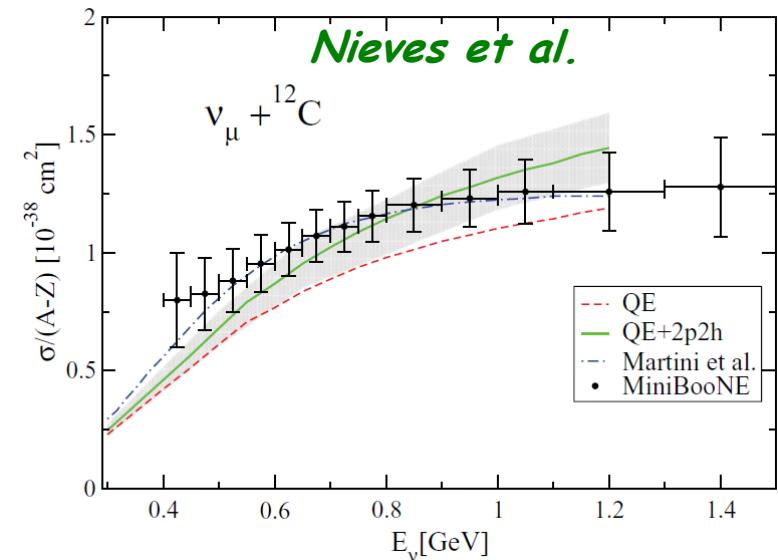
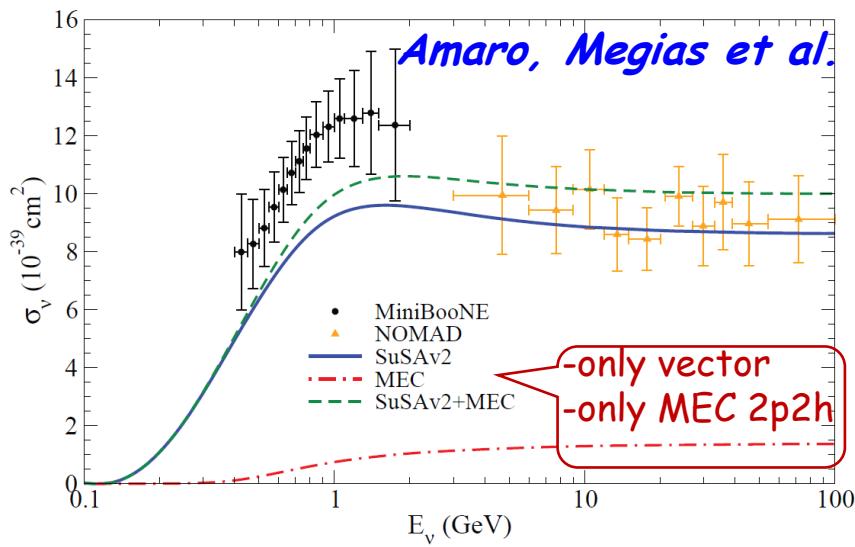
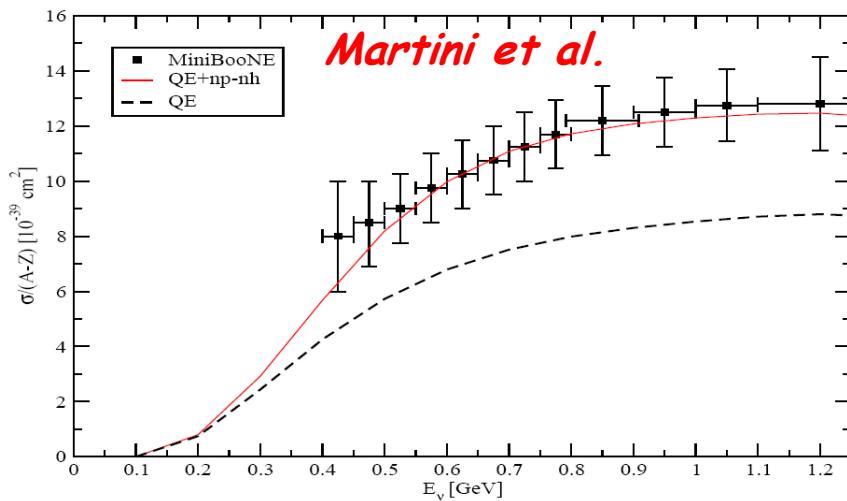
	antineutrino	neutrino	combined fit
including theoretical uncertainties:			
M_A (GeV)	1.16 ± 0.06	1.17 ± 0.06	1.16 ± 0.06
$\chi^2/\text{d.o.f.}$	0.38	1.33	0.93
neglecting theoretical uncertainties:			
M_A (GeV)	1.15 ± 0.10	1.15 ± 0.07	1.13 ± 0.06
$\chi^2/\text{d.o.f.}$	0.44	1.38	1.00
neglecting FSI ($M_A = 1.16$ GeV):			
$\chi^2/\text{d.o.f.}$	2.49	2.45	2.42

MiniBooNE CCQE $d\sigma/d\cos\theta$ $d\sigma/dQ^2$



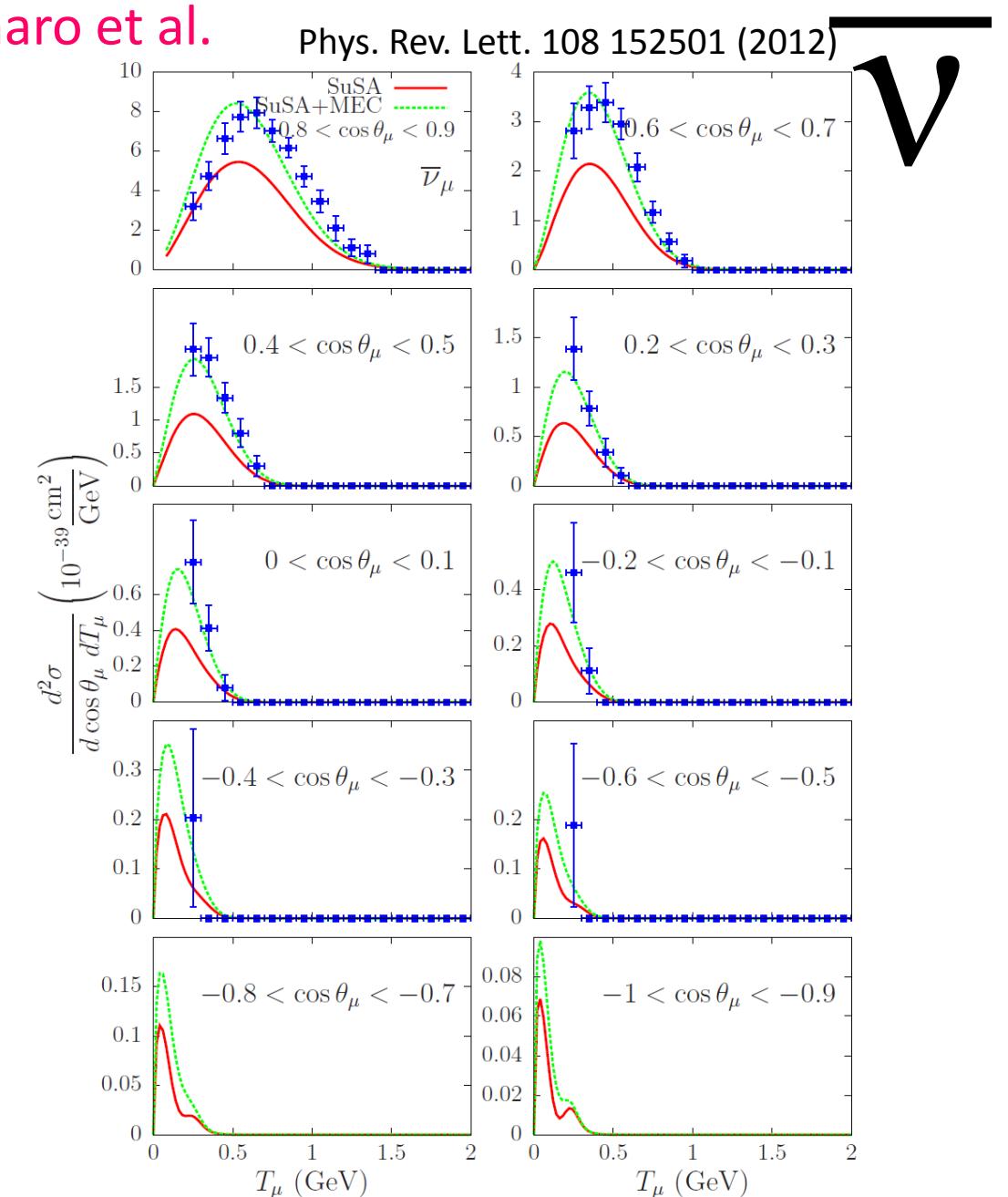
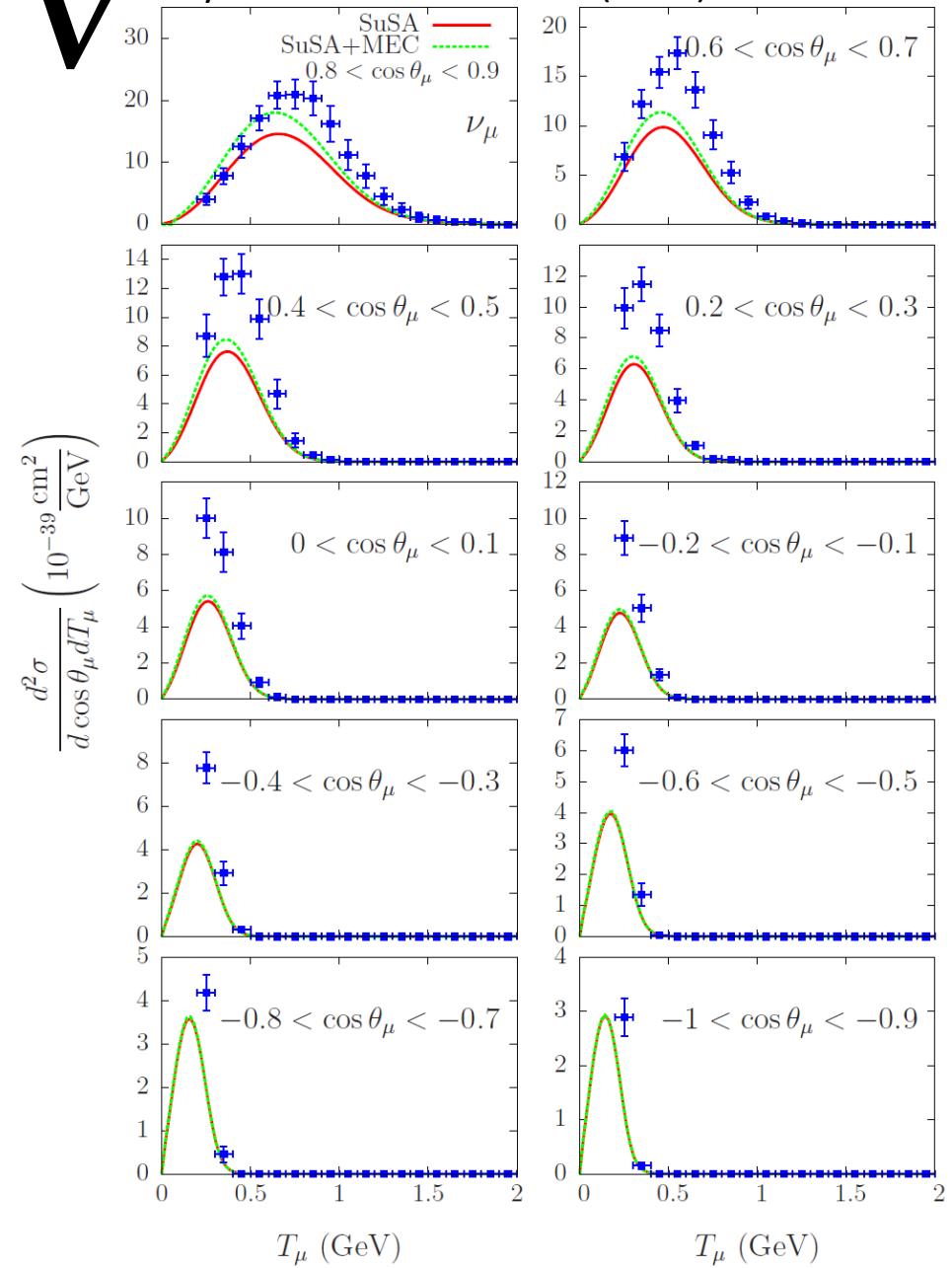
Antineutrino cross section falls more rapidly with angle than the neutrino one

Total CCQE and comparison with flux unfolded MB



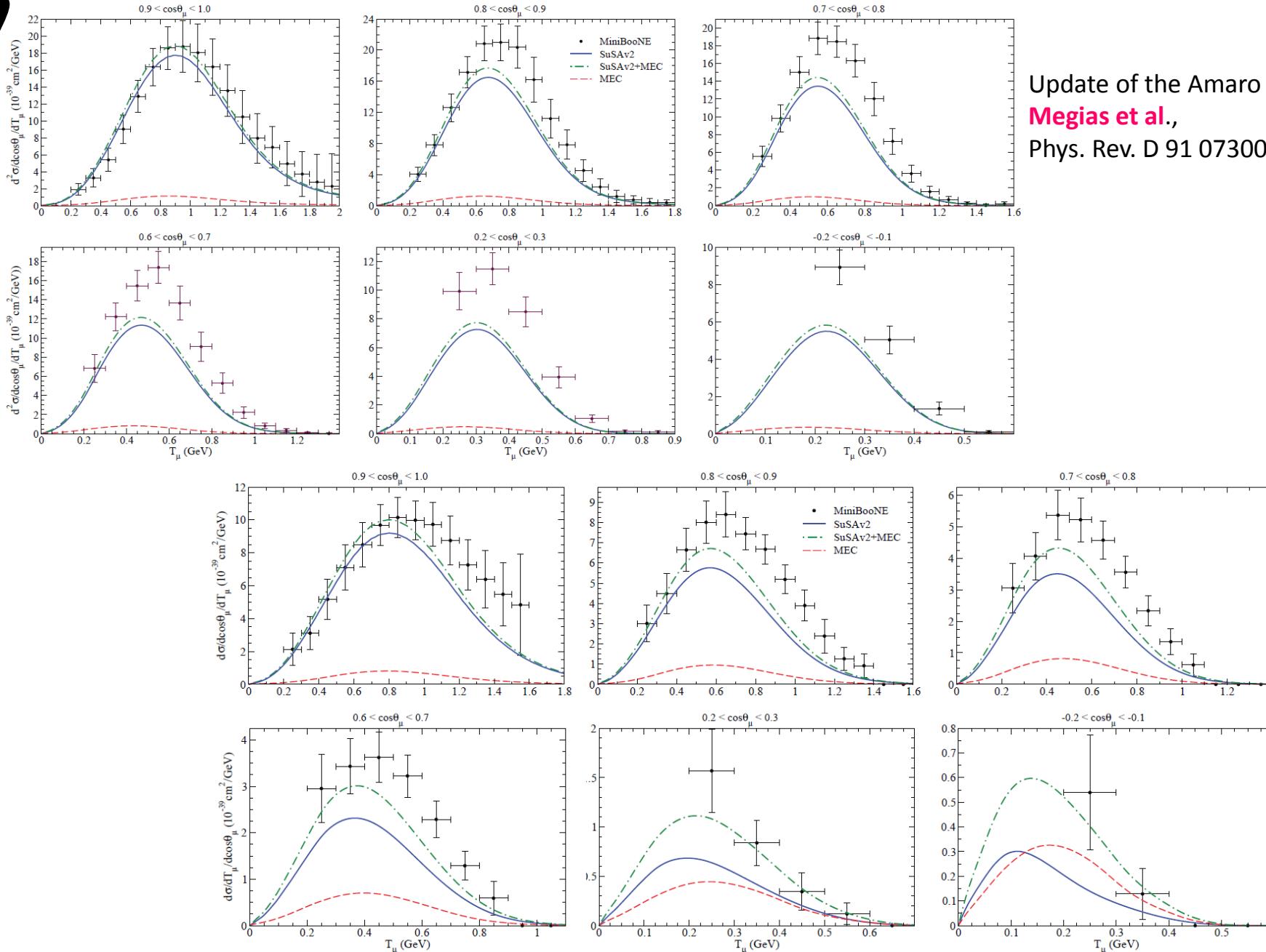
N.B. The experimental unfolding is model dependent

V



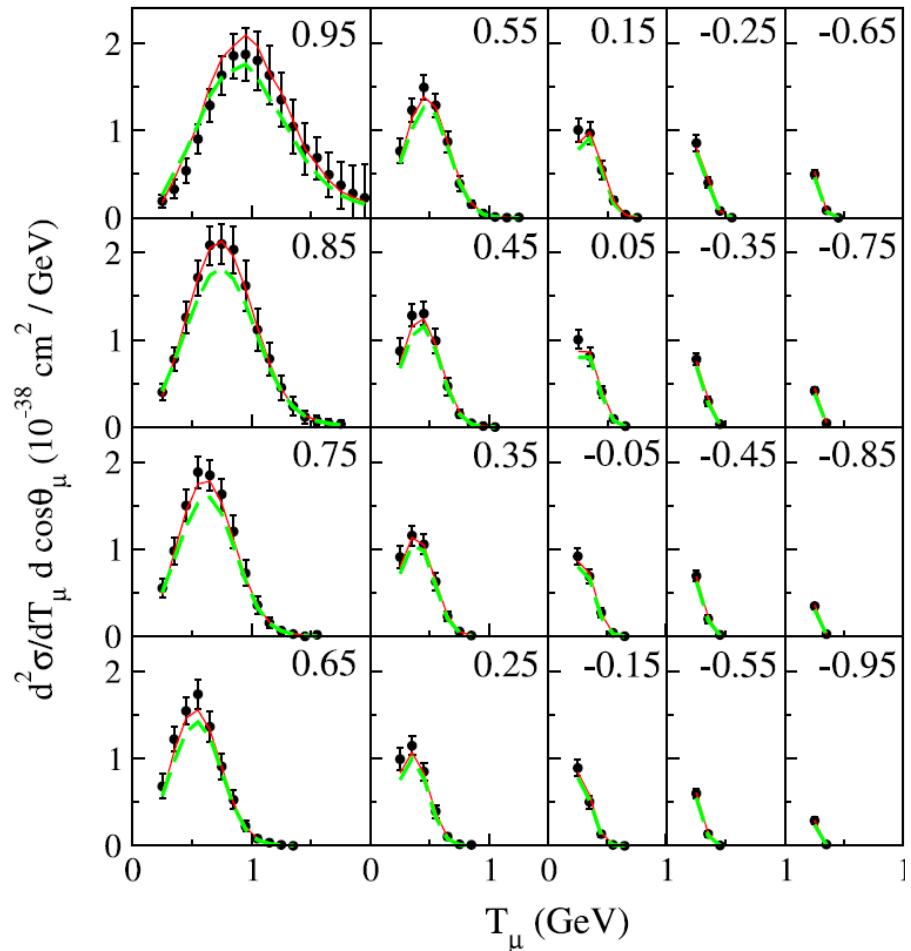
V

V

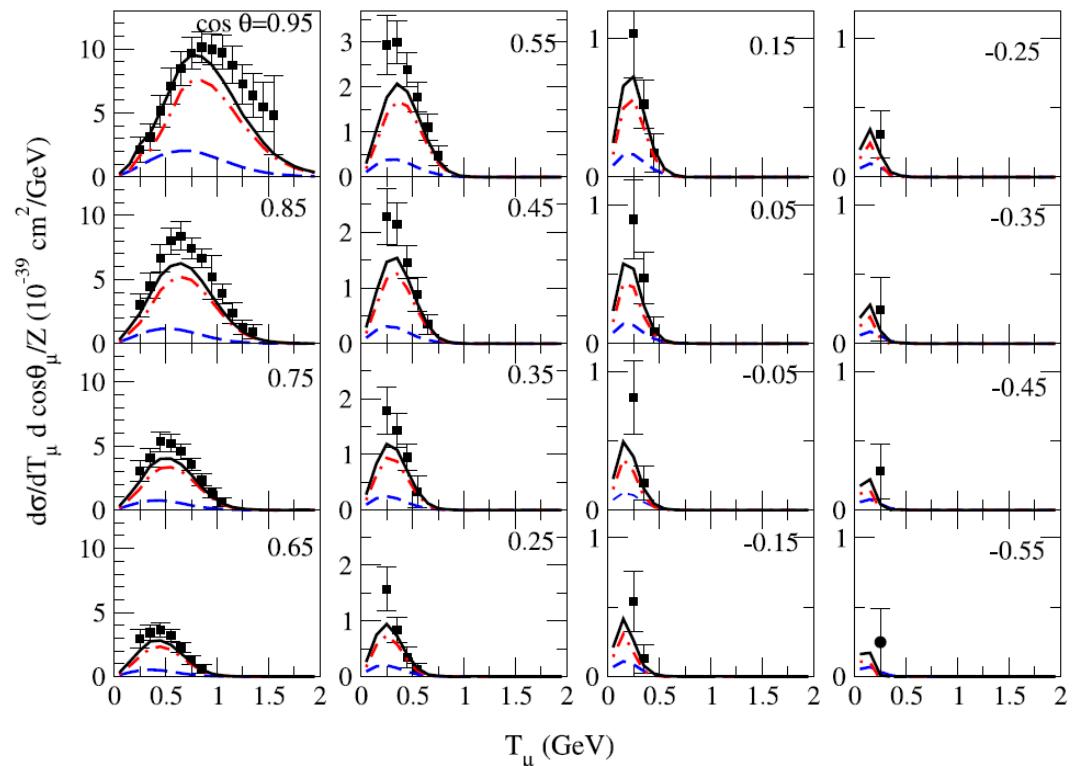


Update of the Amaro et al. results:
Megias et al.,
 Phys. Rev. D 91 073004 (2015)

Phys. Lett. B 707 72-75 (2012)

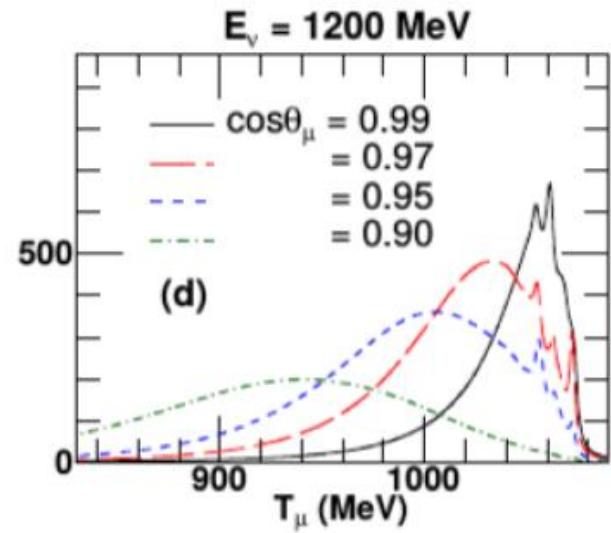
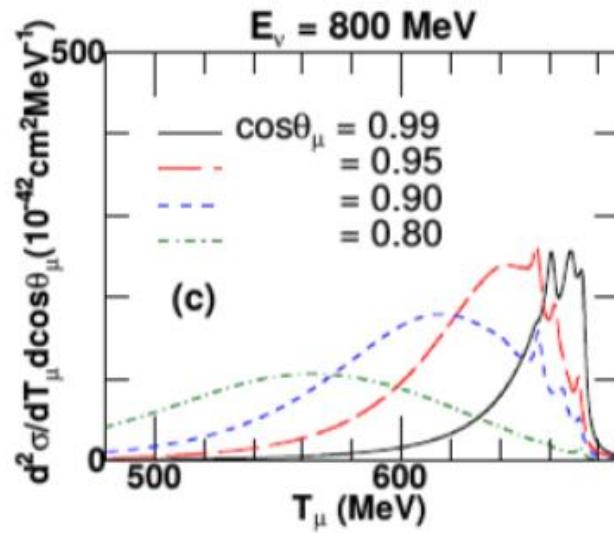
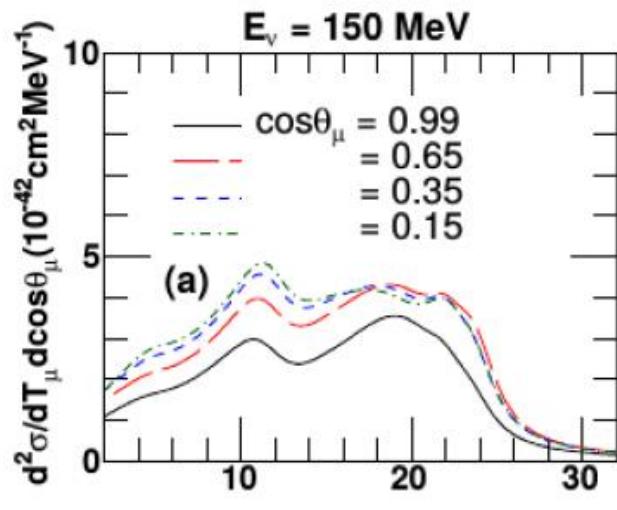


Phys. Lett. B 721 90-93 (2013)



Impact of low-lying giant resonances

CRPA

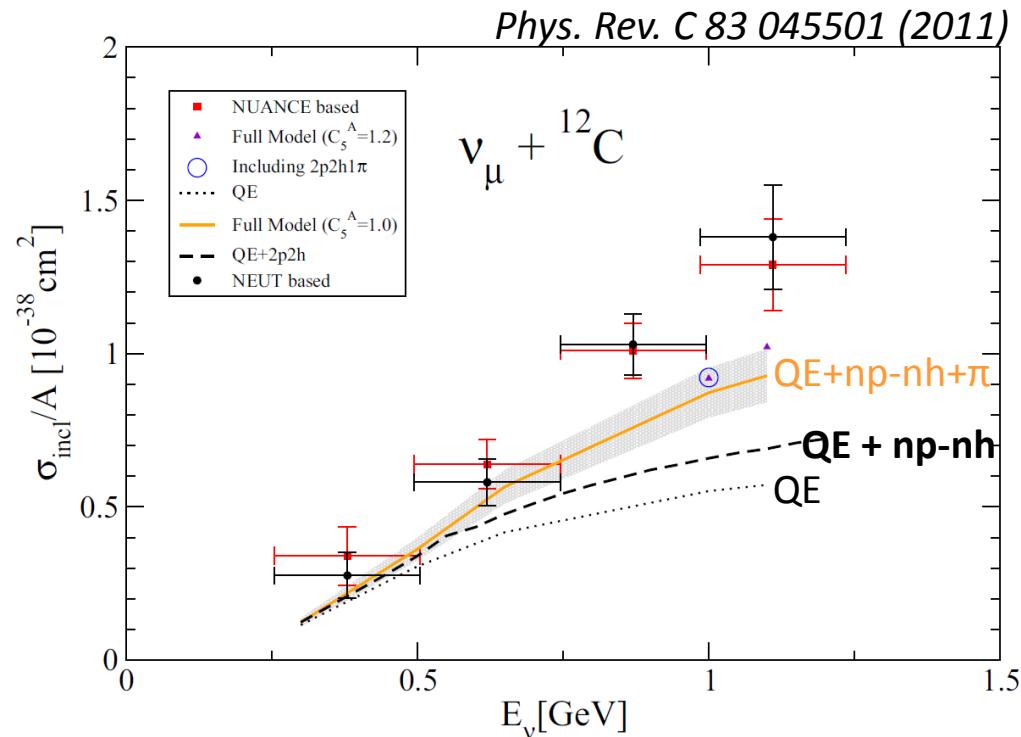
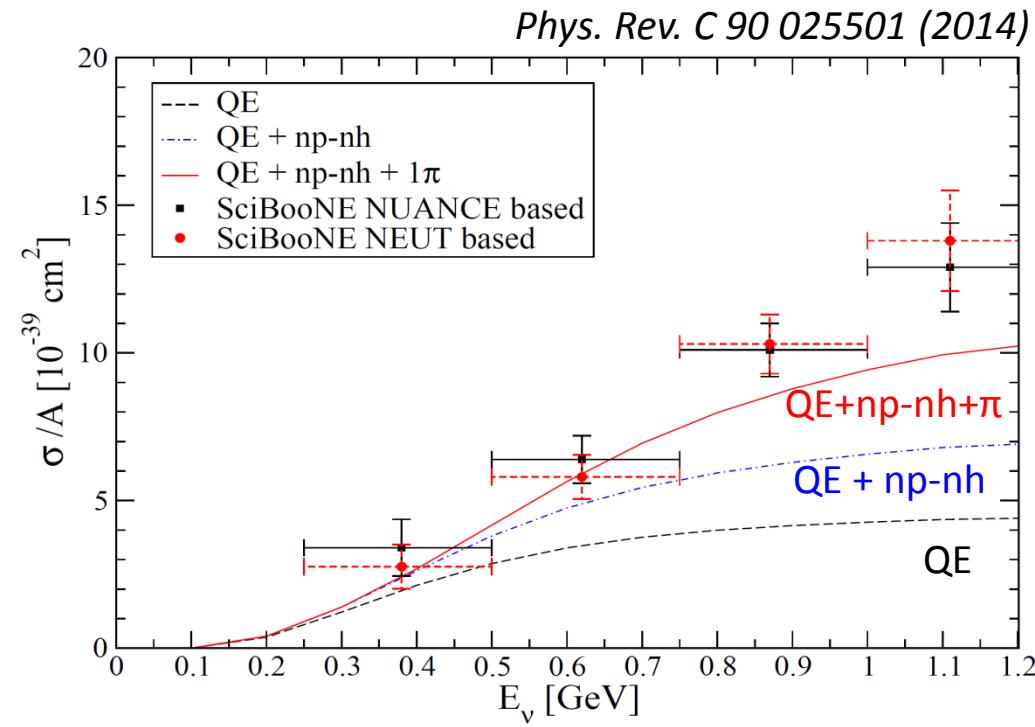


V. Pandey, N. Jachowicz, T. Van Cuyck, J. Ryckebusch, M. Martini, Phys. Rev. C 92, 024606 (2015)

Inclusive CC total cross section on Carbon

Less affected by background subtraction with respect to exclusive channels

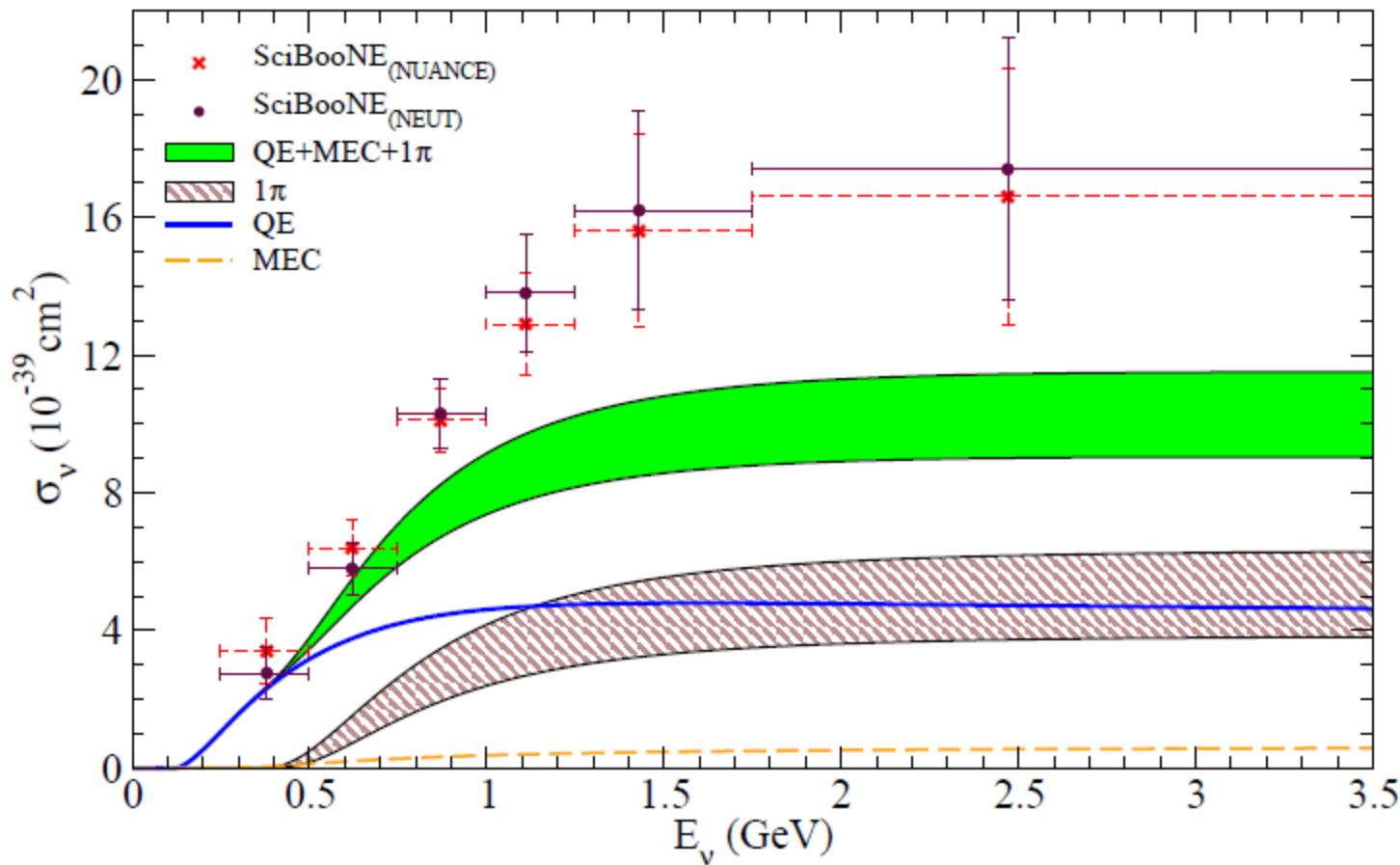
SciBooNE, *Phys. Rev. D* 83, 012005 (2011)



M. Martini, M. Ericson, G. Chanfray, J. Marteau

J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas

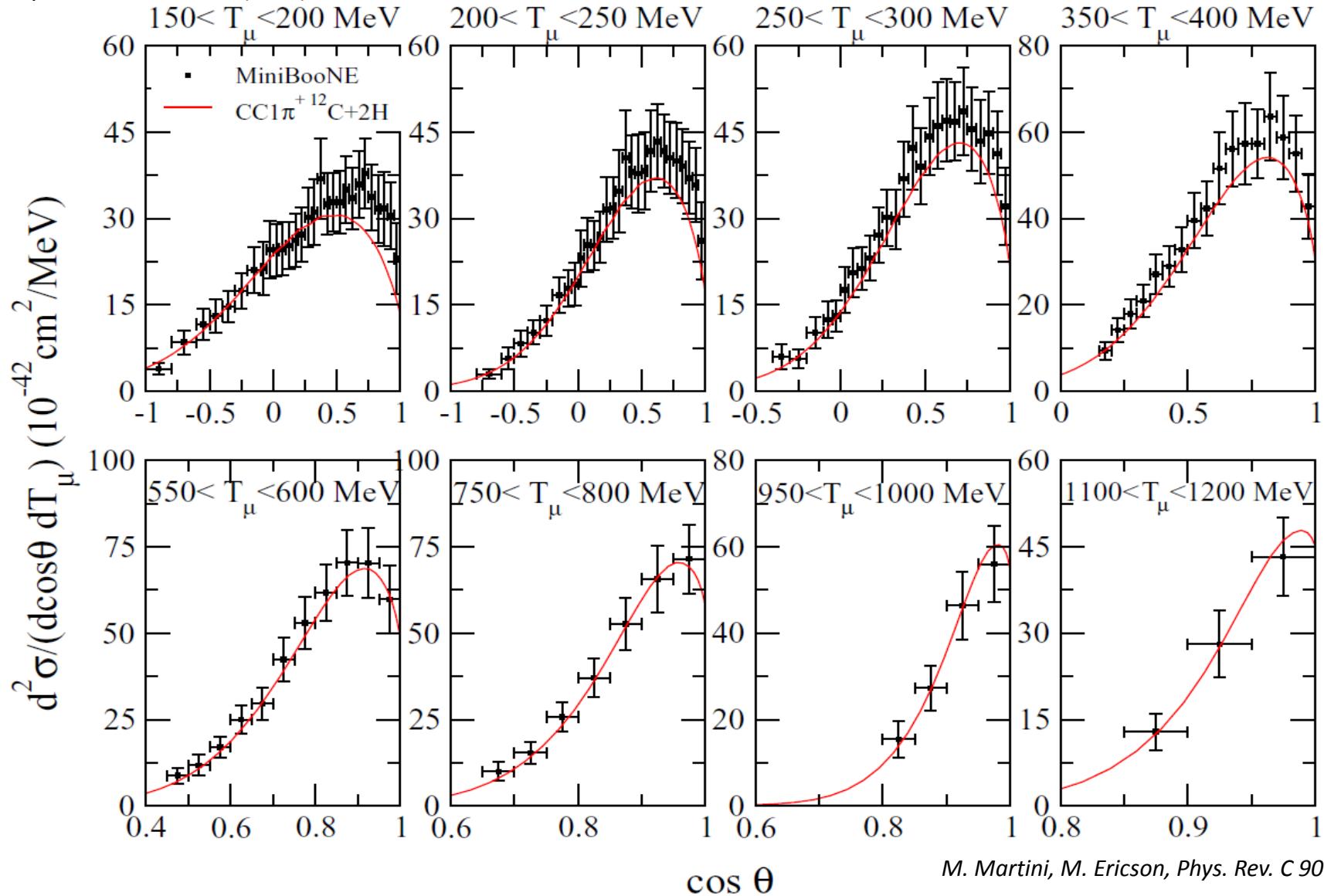
Inclusive CC total cross section on Carbon



Ivanov, Megias et al. arXiv 1506.00801 (2015)

MiniBooNE flux-integrated CC1 π^+ double differential cross section

MiniBooNE Phys. Rev. D 83 052007 (2011)

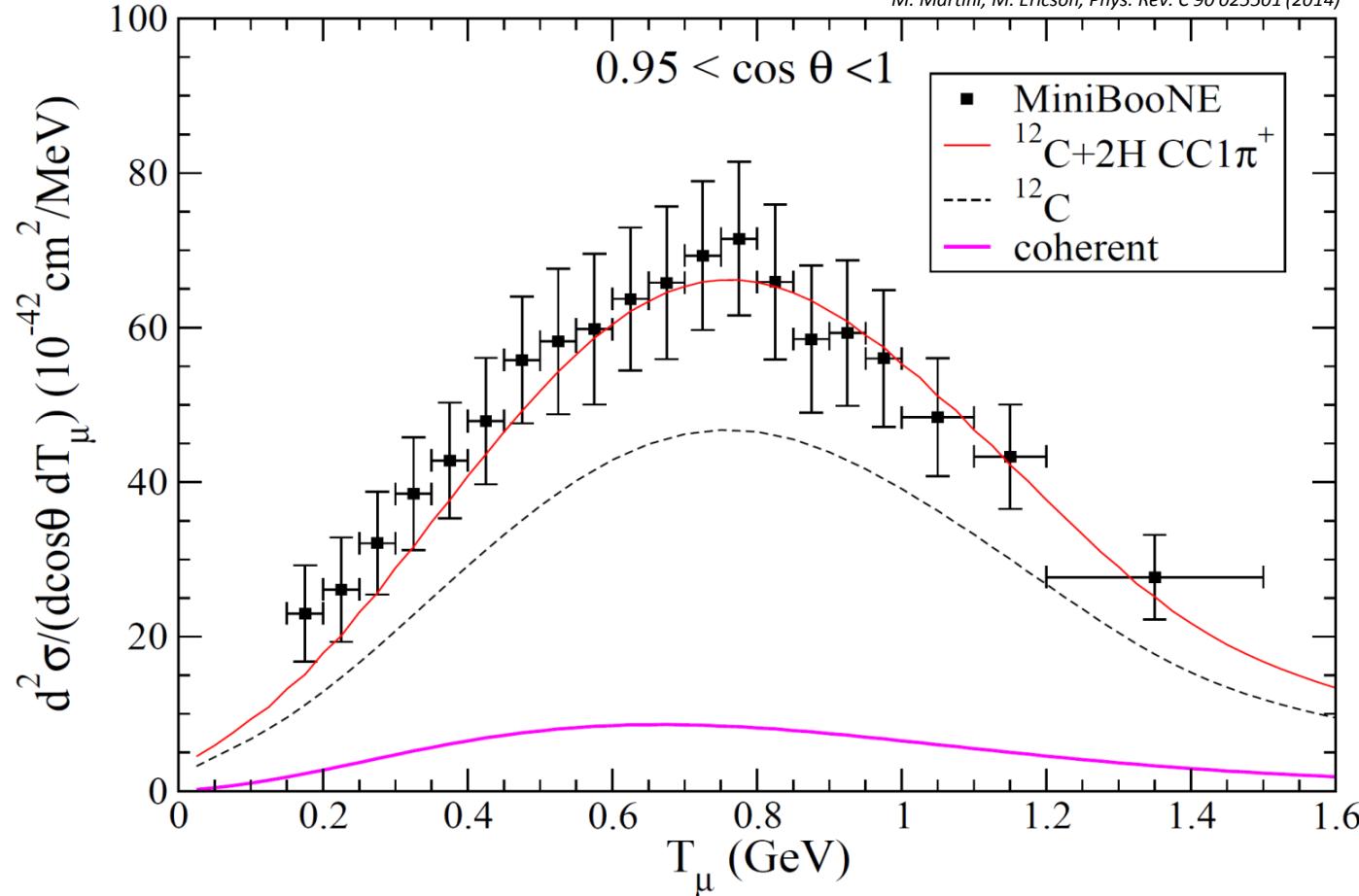


M. Martini, M. Ericson, Phys. Rev. C 90 025501 (2014)

- The general agreement between our evaluation and the data is good.
- Our model does not incorporate the final state interaction for the emitted π on its way out the nucleus

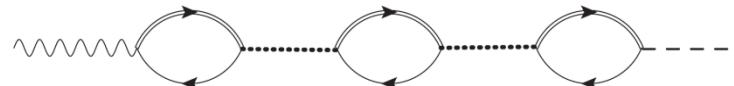
CC1 π^+ double differential cross section in the forward direction

M. Martini, M. Ericson, Phys. Rev. C 90 025501 (2014)



The coherent contribution is significant although not dominant.

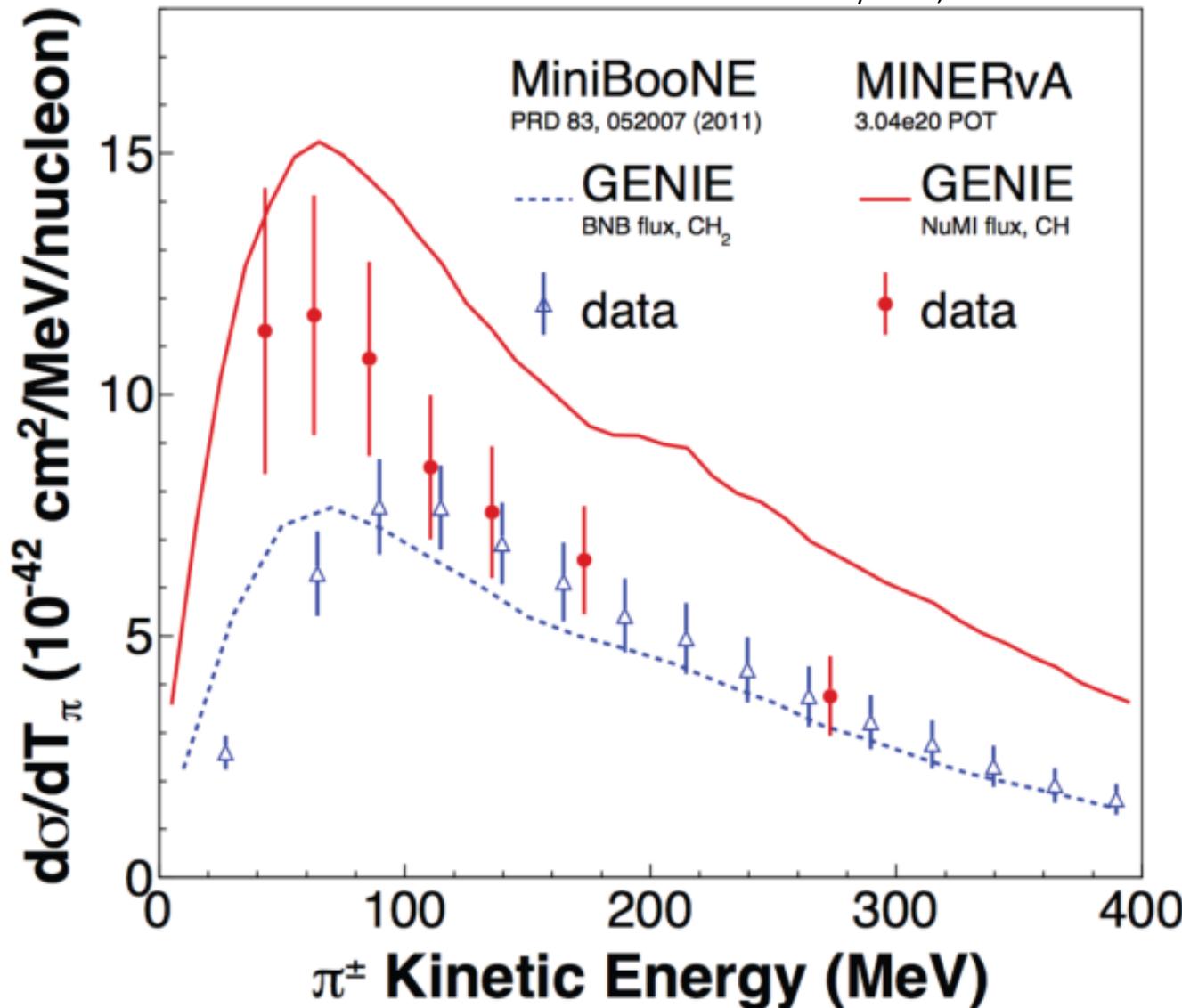
This contribution is interesting due to its relation to a high energy collective state of the nucleus, the **pion branch**, a coherent mixture of Delta-hole states and pions.



It is only in the forward direction that the spin longitudinal response which is sensitive to the pion branch, can dominate the cross section [Delorme and Ericson, PLB 156, 263 (1985)].

MiniBooNE vs MINERvA CC1 π^+ production

Eberly et al. , arXiv:1406.6415



Some theoretical details

Genuine Quasielastic Scattering

Nucleon-Nucleon interaction switched off

Nucleons respond individually

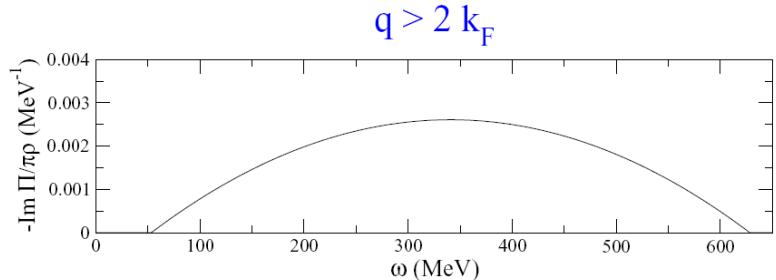
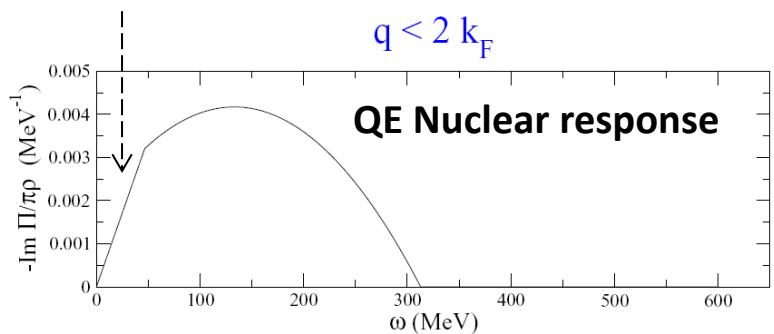
Nucleon at rest:

$$R\alpha \delta(\omega - (\sqrt{q^2 + M^2} - M))$$

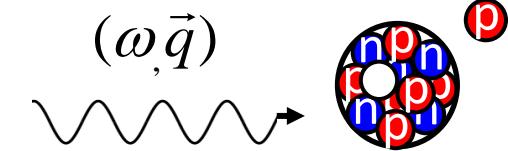
Nucleon inside the nucleus:

Fermi motion spreads δ distribution (Fermi Gas)

Pauli blocking cuts part of the low momentum Resp.



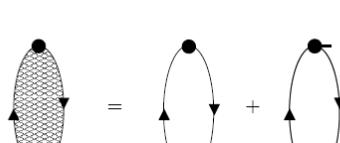
10/8/2015



Nucleon-Nucleon interaction switched on

The nuclear response becomes collective

Random Phase Approximation

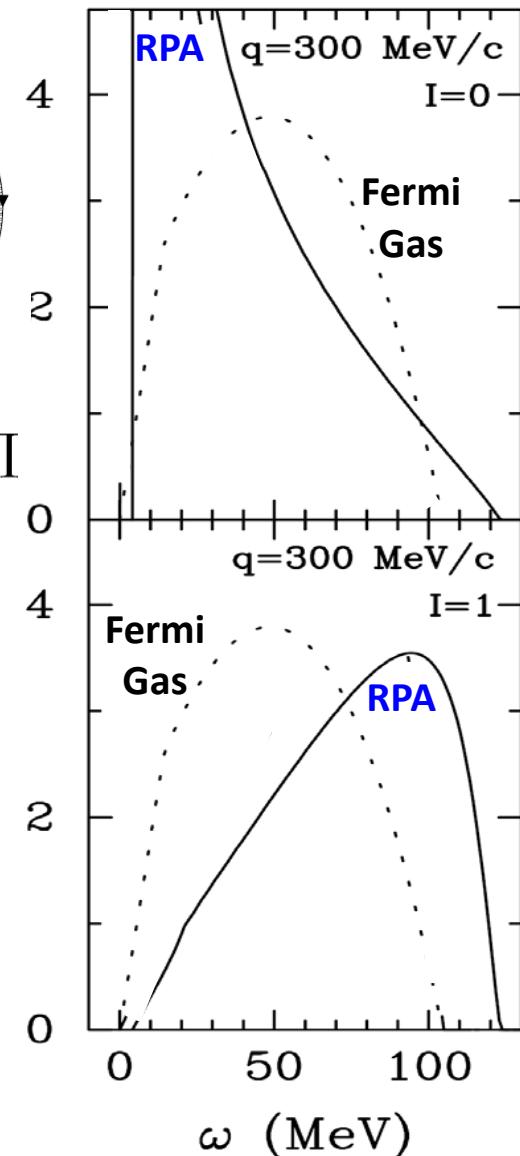


$$\Pi = \Pi^0 + \Pi^0 V \Pi$$

*Force acting on one nucleon is transmitted by the interaction

*Shift of the peak with respect to Fermi Gas, decrease, increase,...

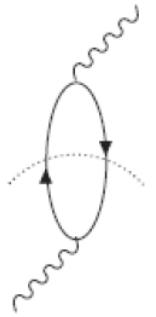
Alberico, Ericson, Molinari,
Nucl. Phys. A 379, 429 (1982)



M. Martini, NuFact15

Bare polarization propagators

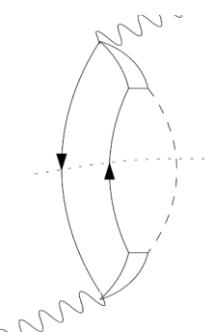
Quasielastic



$$\Pi^0(\vec{q}, \omega) = g \int \frac{d\vec{k}}{(2\pi)^3} \left[\frac{\theta(|\vec{k} + \vec{q}| - k_F) \theta(k_F - k)}{\omega - (\omega_{\vec{k}+\vec{q}} - \omega_{\vec{k}}) + i\eta} - \frac{\theta(k_F - |\vec{k} + \vec{q}|) \theta(k - k_F)}{\omega + (\omega_{\vec{k}} - \omega_{\vec{k}+\vec{q}}) - i\eta} \right]$$

Nucleon-hole

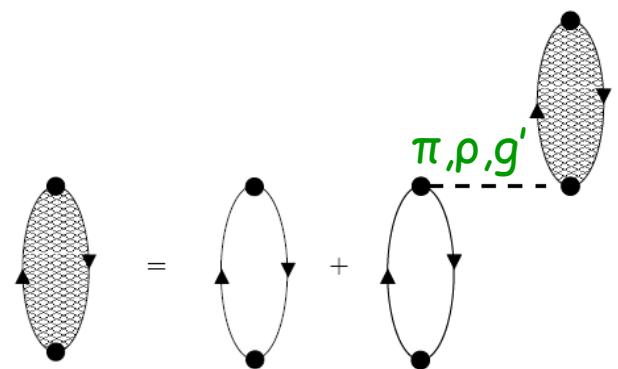
Pion production



$$\Pi_{\Delta-h}(q) = \frac{32\tilde{M}_\Delta}{9} \int \frac{d^3 k}{(2\pi)^3} \theta(k_F - k) \left[\frac{1}{s - \tilde{M}_\Delta^2 + i\tilde{M}_\Delta \Gamma_\Delta} - \frac{1}{u - \tilde{M}_\Delta^2} \right]$$

Delta-hole

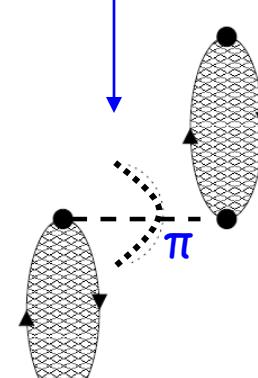
Switching on the interaction: random phase approximation



RPA

$$\Pi = \Pi^0 + \Pi^0 V \Pi$$

$$\text{Im}\Pi = |\Pi|^2 \text{ Im}V + |1 + \Pi V|^2 \text{ Im}\Pi^0$$

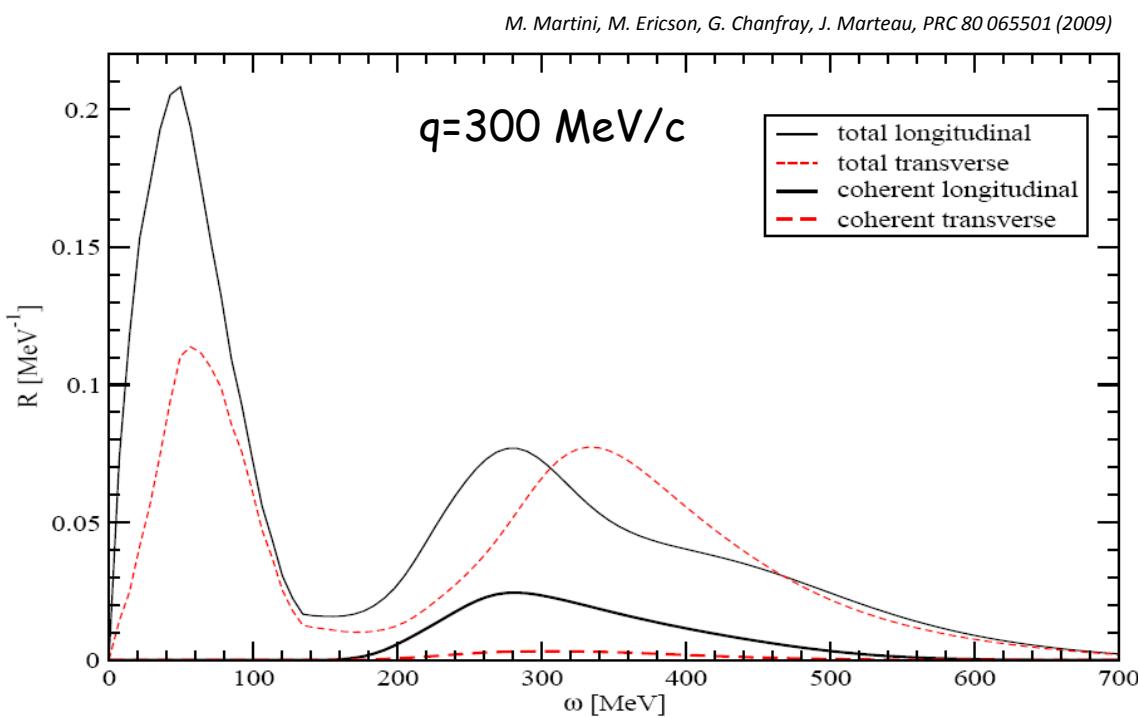


$$\Pi^0 = \sum_{k=1}^{N_k} \Pi_{(k)}^0$$

exclusive channels:
QE, 2p-2h, $\Delta \rightarrow \pi N$...

coherent π
production

Several partial components
treated in self-consistent,
coupled and coherent way



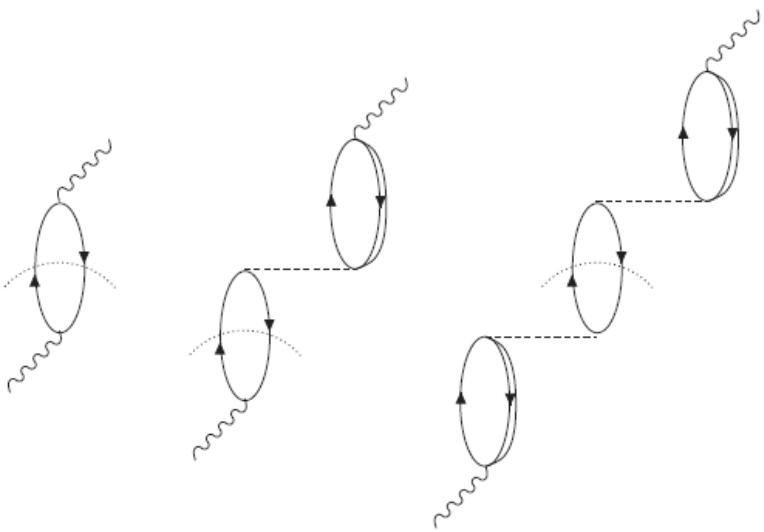
Effects of the RPA in the ν genuine quasielastic scattering

QE totally dominated by isospin spin-transverse response $R_{\sigma\tau(T)}$

RPA reduction

- expected from the repulsive character of p-h interaction in T channel
- mostly due to interference term $R^{N\Delta} < 0$
(Lorentz-Lorenz or Ericson-Ericson effect)

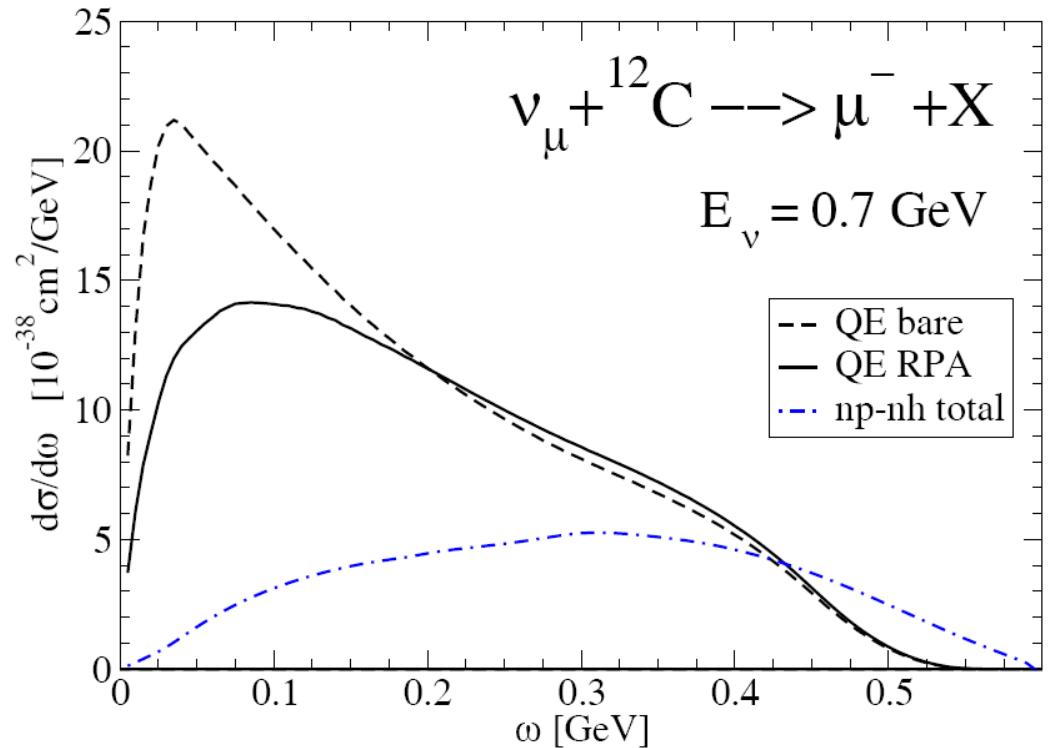
Lowest order contribution to QE



$$R_{QE}^{NN}$$

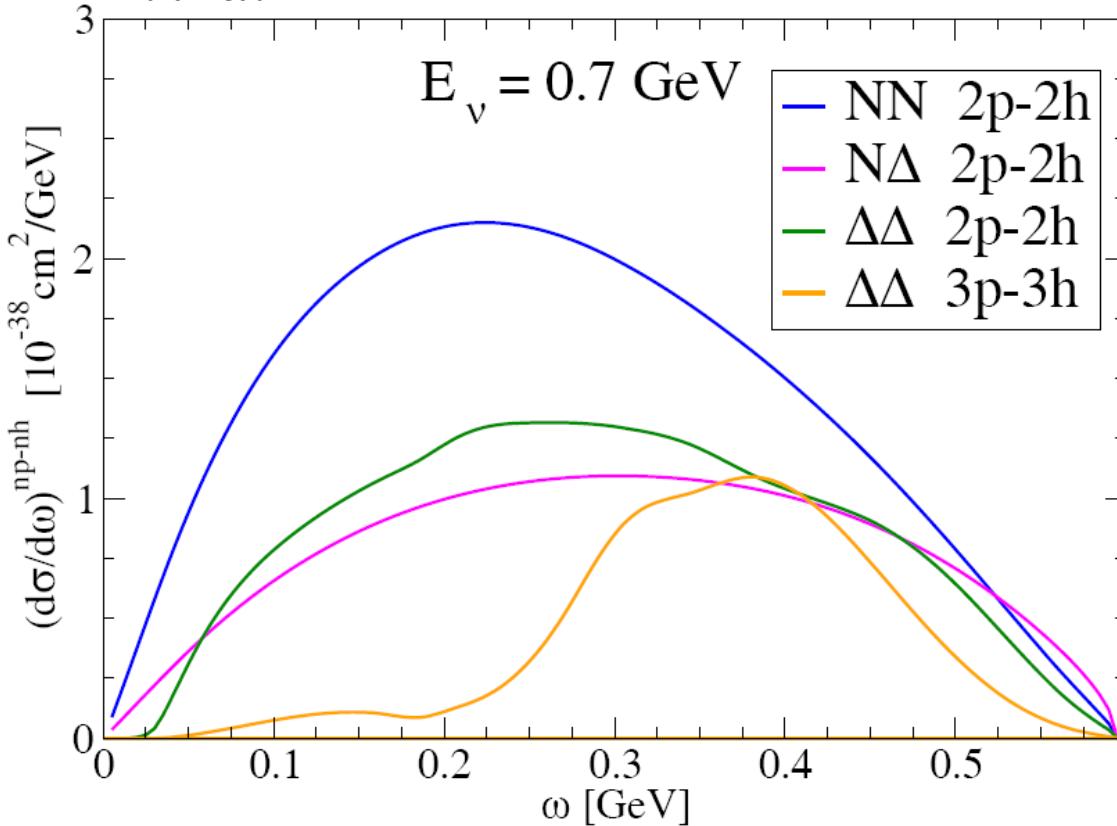
$$R_{QE}^{ND}$$

$$R_{QE}^{\Delta\Delta}$$

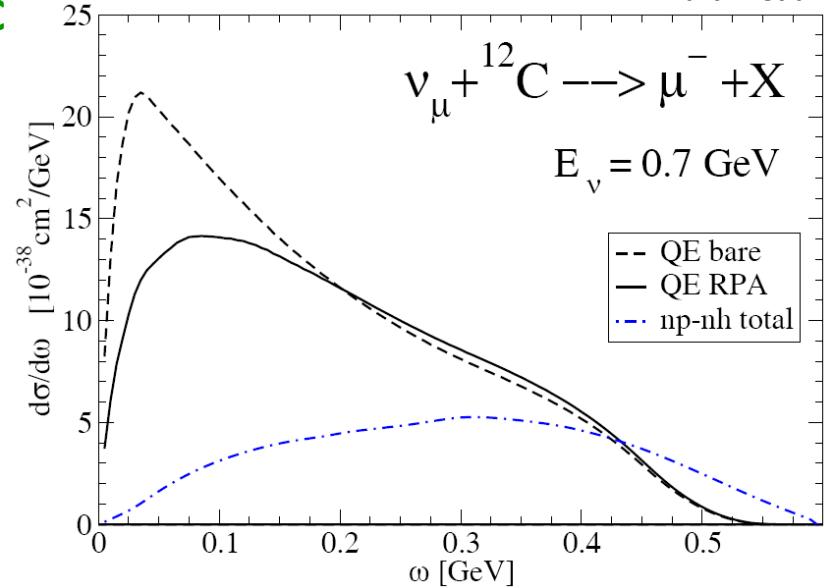


Different contributions in the np-nh channel

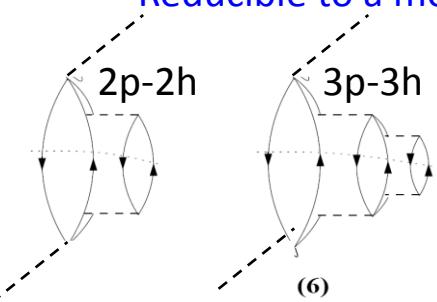
Martini et al.



Correlations
Interference
MEC

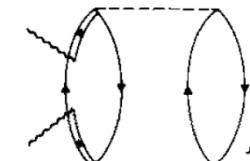


- Reducible to a modification of the Δ width in the medium

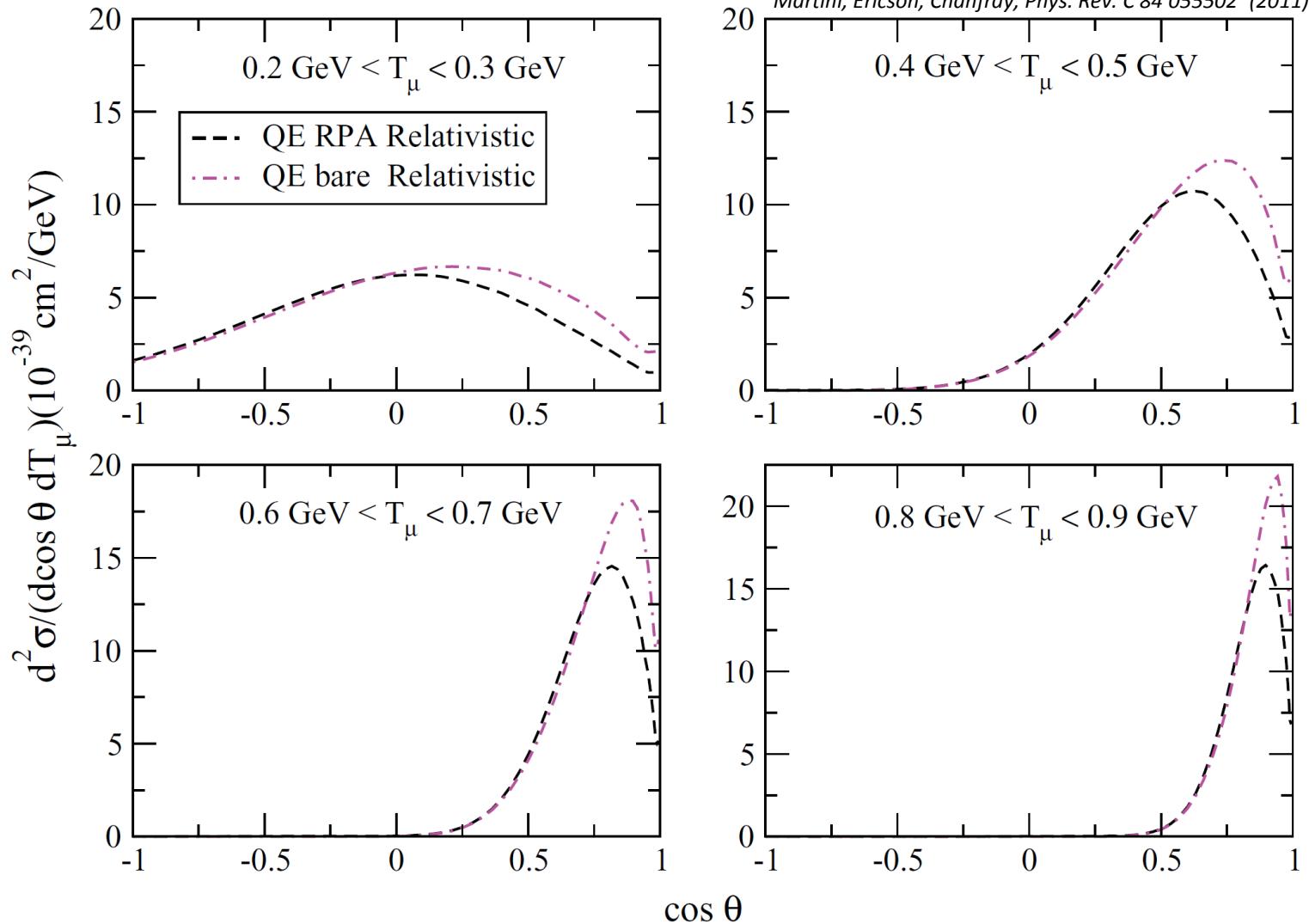


From:
 E. Oset and L. L. Salcedo, NPA 468, 631 (1987)
 in Martini et al, Nieves et al and also in the T2K analyses.

- Not reducible to a modification of the Δ width



Bare vs RPA for MiniBooNE flux folded $d^2\sigma$ (genuine QE)



RPA produces a quenching and some shift towards larger angles

Neutrino-nucleus cross section

Two equivalent expressions:

The notation for example of Amaro et al:

$$\frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = \sigma_0 [L_{CC}(R_{CC}^V + R_{CC}^A) + L_{CL}(R_{CL}^V + R_{CL}^A) + L_{LL}(R_{LL}^V + R_{LL}^A) + L_T(R_T^V + R_T^A) \pm L_{T'VA}R_{T'}^{VA}]$$

Longitudinal

Transverse

Transverse

V-A interference

The notation of Lovato et al:

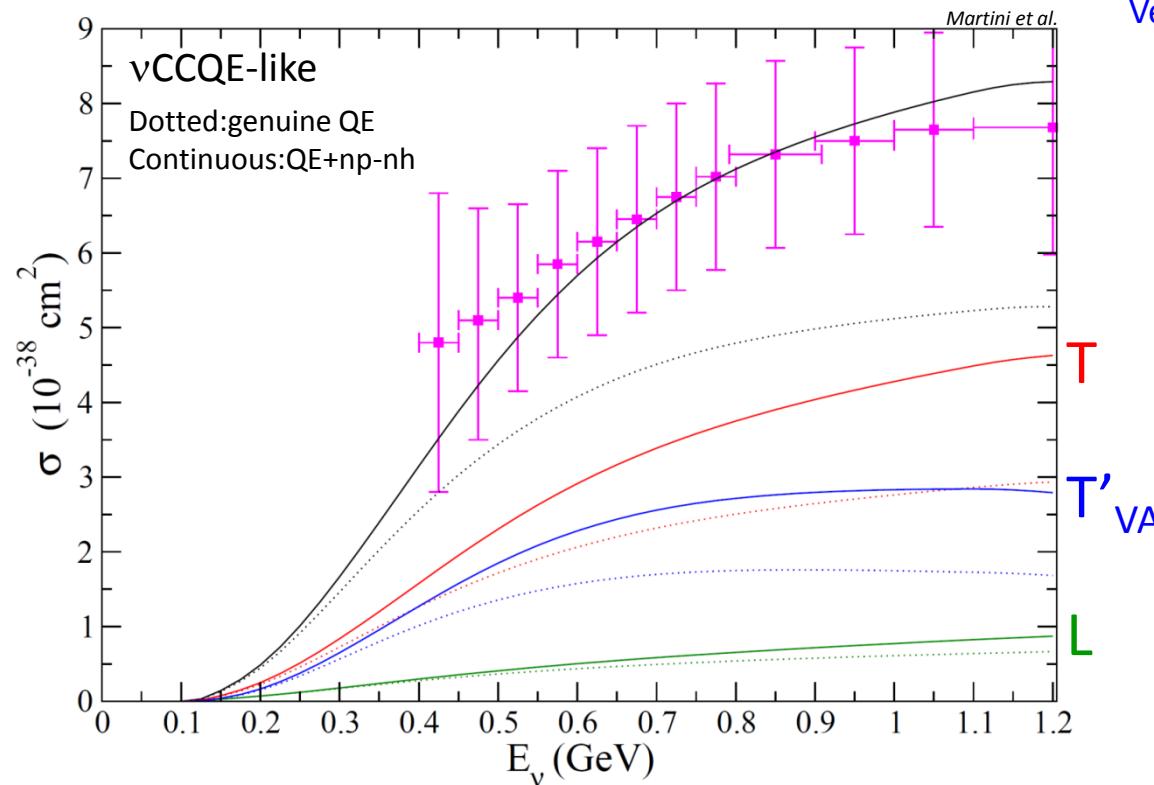
$$\frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = \sigma_0 [L_{00}R_{00} + L_{0z}R_{0z} + L_{zz}R_{zz} + L_{xx}R_{xx} \pm L_{xy}R_{xy}]$$

Longitudinal

Transverse

Transverse

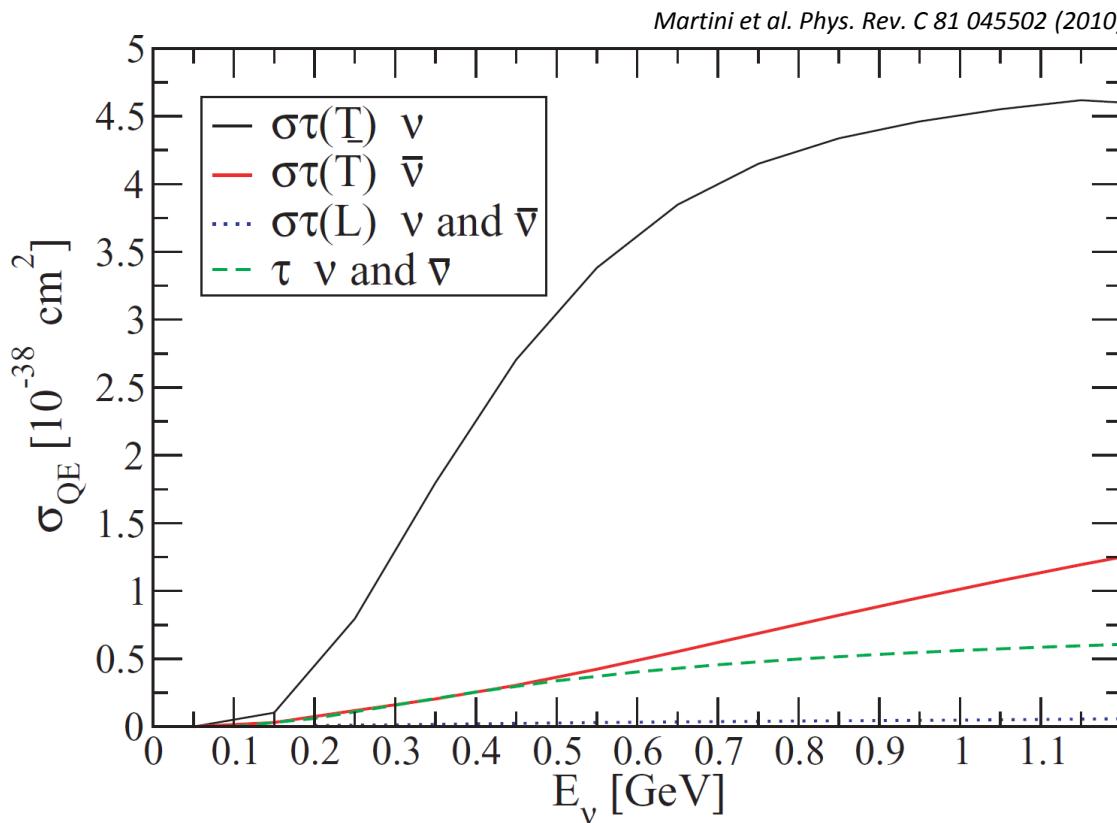
Vector-Axial interference



A third simplified expression (useful for illustration)

Resp. Functions: Charge $R_\tau(\tau)$, Isospin Spin-Longitudinal $R_{\sigma\tau(L)}(\tau \sigma \cdot q)$, Isospin Spin Transverse $R_{\sigma\tau(T)}(\tau \sigma \times q)$

$$\begin{aligned} \frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = & \frac{G_F^2 \cos^2 \theta_c}{2 \pi^2} k' \epsilon' \cos^2 \frac{\theta}{2} \left[\frac{(q^2 - \omega^2)^2}{q^4} G_E^2 R_\tau + \frac{\omega^2}{q^2} G_A^2 R_{\sigma\tau(L)} + \right. \\ & + 2 \left(\tan^2 \frac{\theta}{2} + \frac{q^2 - \omega^2}{2q^2} \right) \left(G_M^2 \frac{\omega^2}{q^2} + G_A^2 \right) \underline{R_{\sigma\tau(T)}} \pm 2 \frac{\epsilon + \epsilon'}{M_N} \tan^2 \frac{\theta}{2} G_A G_M \underline{\underline{R_{\sigma\tau(T)}}} \end{aligned}$$



The relative weight of the 3 different nuclear responses (R_τ , $R_{\sigma\tau(L)}$, $R_{\sigma\tau(T)}$) is different for neutrinos and antineutrinos due to the Vector-Axial interference term

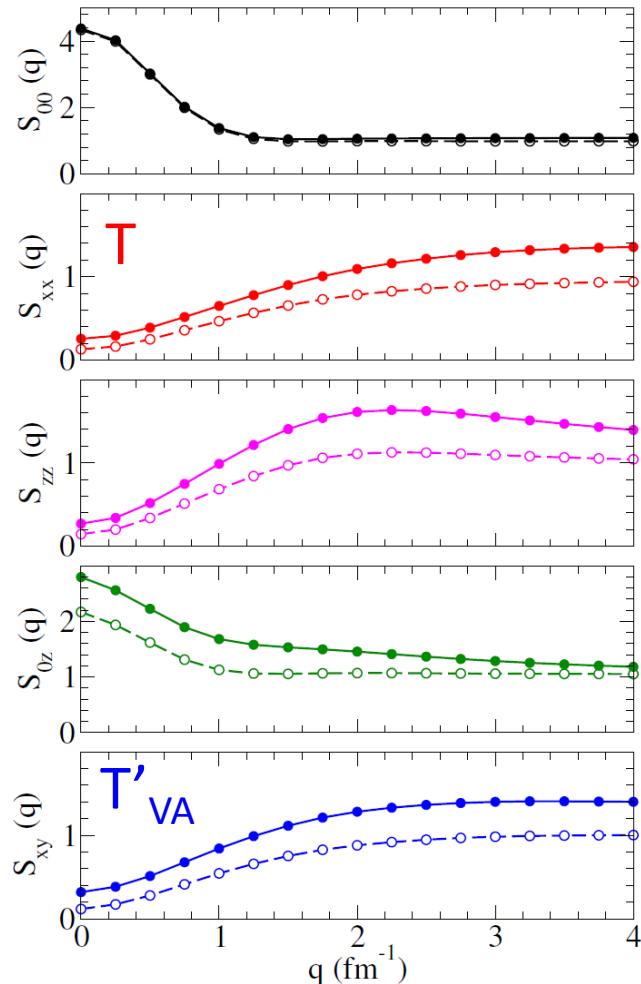
$$\begin{cases} + & (\nu) \\ - & (\bar{\nu}) \end{cases}$$

Some instructive comparisons (of two different quantities)

Sum rules of NC

$$S_{\alpha\beta}(q) = C_{\alpha\beta} \int_{\omega_{\text{el}}}^{\infty} d\omega R_{\alpha\beta}(q, \omega)$$

Lovato et al. PRL 112 182502 (2014)

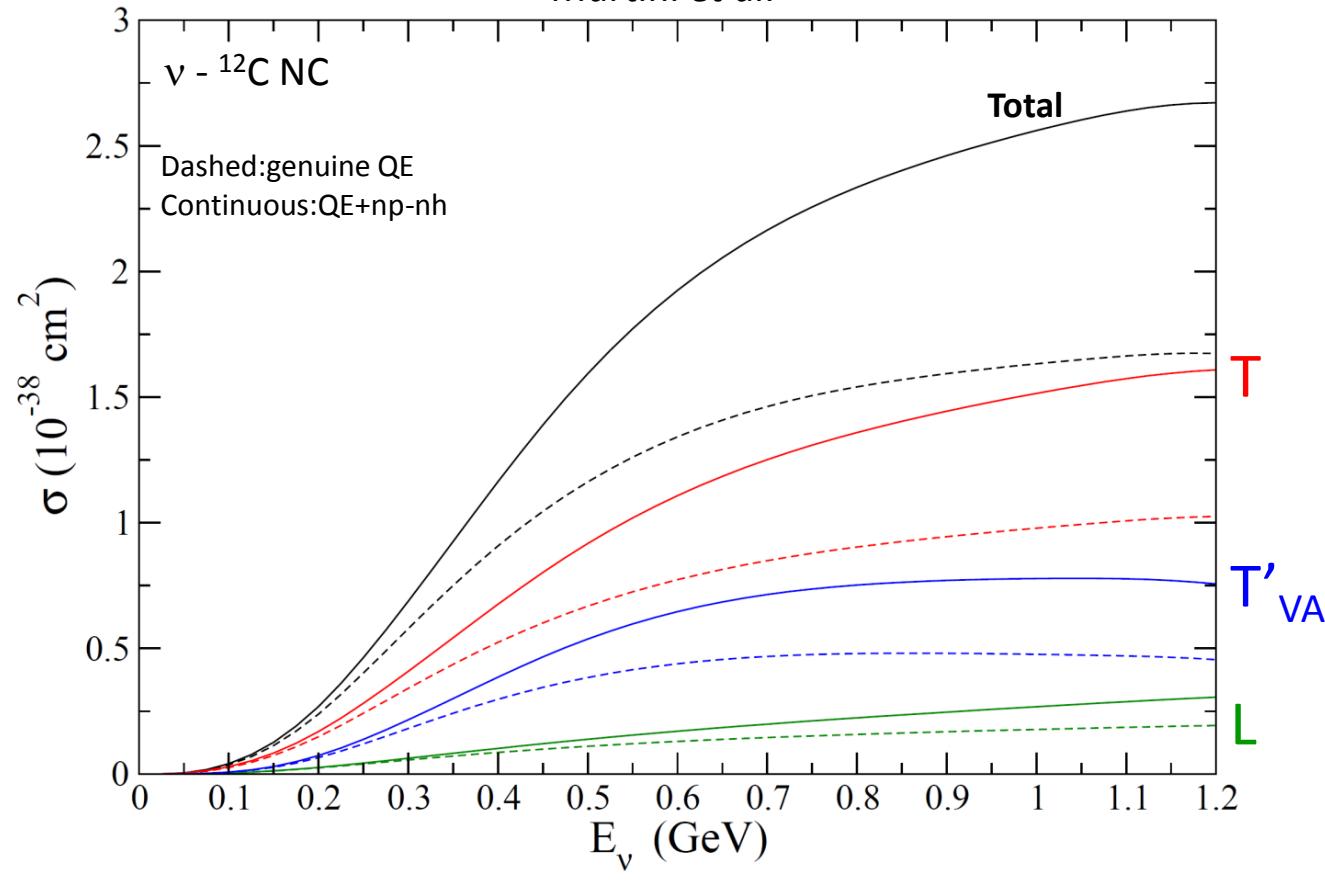


Cross section

$$\frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = \sigma_0 [L_{00}R_{00} + L_{0z}R_{0z} + L_{zz}R_{zz} + L_{xx}R_{xx} \pm L_{xy}R_{xy}]$$

Transverse Transverse
Longitudinal VA Interf.

Martini et al.



In both approaches 2p-2h are important in **all components** (but the charge)

Where 2p-2h contributions enter in the different approaches

Martini et al.

Nieves et al.

Amaro et al.

Lovato et al.

Bodek et al.

[Follow the color and the style of the lines:]

$$\frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = \sigma_0 [L_{CC}(R_{CC}^V + R_{CC}^A) + L_{CL}(R_{CL}^V + R_{CL}^A) + L_{LL}(R_{LL}^V + R_{LL}^A) + L_T(R_T^V + R_T^A) \pm L_{T'VA}R_{T'}^{VA}]$$

$$\frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = \sigma_0 [L_{00}R_{00} + L_{0z}R_{0z} + L_{zz}R_{zz} + L_{xx}R_{xx} \pm L_{xy}R_{xy}]$$

$$\begin{aligned} \frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} &= \frac{G_F^2 \cos^2 \theta_c}{2 \pi^2} k' \epsilon' \cos^2 \frac{\theta}{2} \left[\frac{(q^2 - \omega^2)^2}{q^4} G_E^2 R_\tau + \frac{\omega^2}{q^2} G_A^2 R_{\sigma\tau(L)} + \right. \\ &+ 2 \left(\tan^2 \frac{\theta}{2} + \frac{q^2 - \omega^2}{2q^2} \right) \left(G_M^2 \frac{\omega^2}{q^2} + G_A^2 \right) R_{\sigma\tau(T)} \left. \pm 2 \frac{\epsilon + \epsilon'}{M_N} \tan^2 \frac{\theta}{2} G_A G_M R_{\sigma\tau(T)} \right] \end{aligned}$$

Relative role of 2p-2h for neutrinos and antineutrinos is different due to the interference term

Neutrino scattering

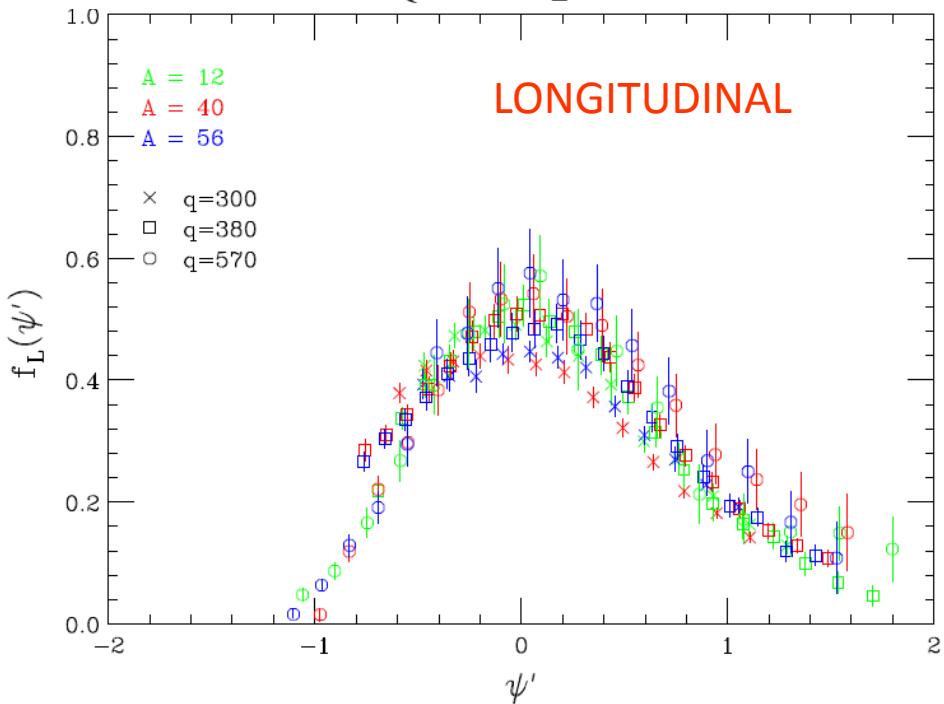
$$\frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = \frac{G_F^2 \cos^2 \theta_c}{2 \pi^2} k' \epsilon' \cos^2 \frac{\theta}{2} \left[\frac{(q^2 - \omega^2)^2}{q^4} G_E^2 R_\tau + \frac{\omega^2}{q^2} G_A^2 R_{\sigma\tau(L)} + \right.$$

$$+ 2 \left(\tan^2 \frac{\theta}{2} + \frac{q^2 - \omega^2}{2q^2} \right) \left(G_M^2 \frac{\omega^2}{q^2} + G_A^2 \right) \left. \frac{R_{\sigma\tau(T)}}{\dots} \pm 2 \frac{\epsilon + \epsilon'}{M_N} \tan^2 \frac{\theta}{2} G_A G_M R_{\sigma\tau(T)} \right]$$

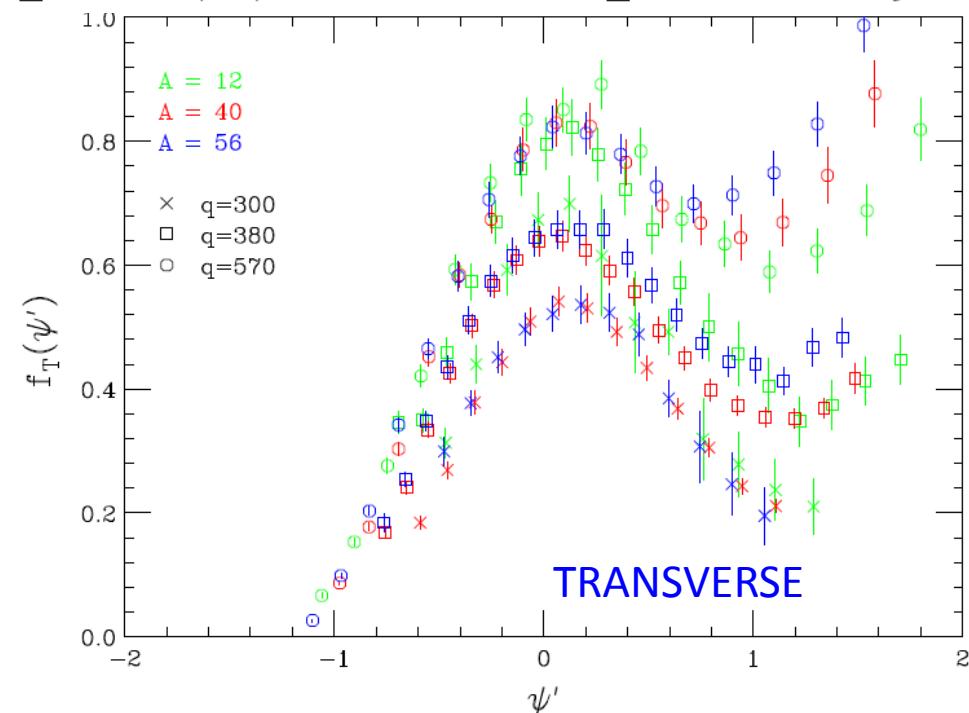
Electron scattering

$$\frac{d^2\sigma}{d\theta d\omega} = \sigma_M \left\{ \frac{(\omega^2 - q^2)^2}{q^4} R_L(\omega, q) \right. +$$

$$+ \left[\tan^2 \left(\frac{\theta}{2} \right) - \frac{\omega^2 - q^2}{2q^2} \right] \boxed{R_T(\omega, q)}$$



Donnelly et al. PRC 60 '99, ...

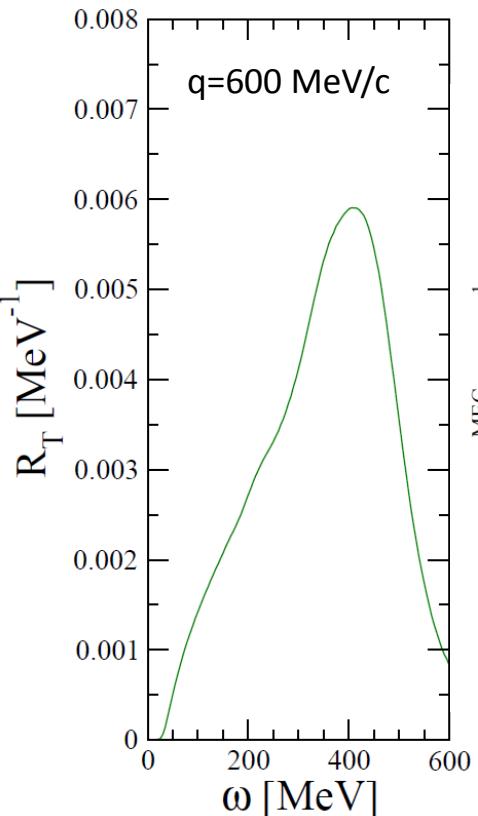


Excess in the transverse channel likely due to 2-body currents (MEC and correlations)

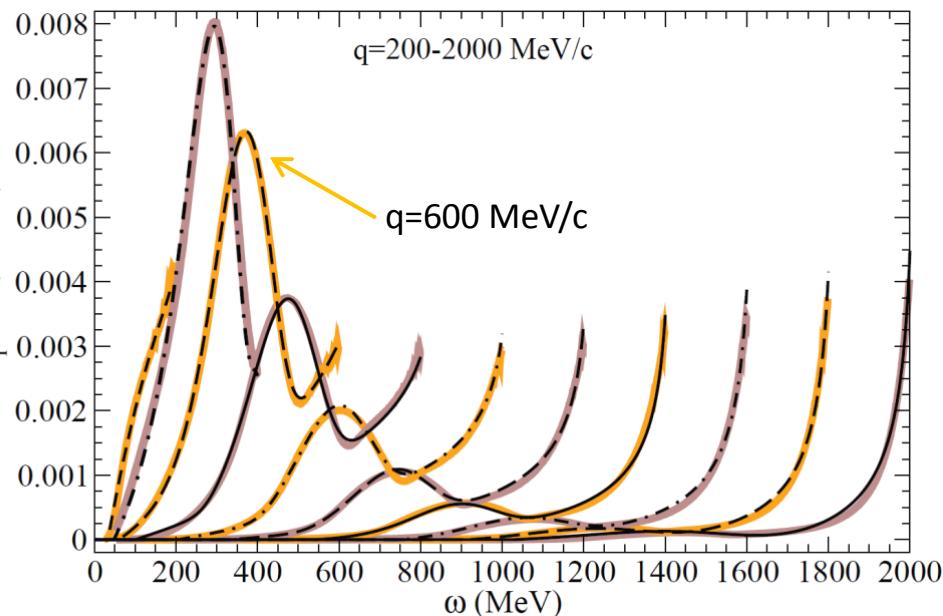
2p-2h MEC contribution to the electromagnetic transverse response

2p-2h MEC only

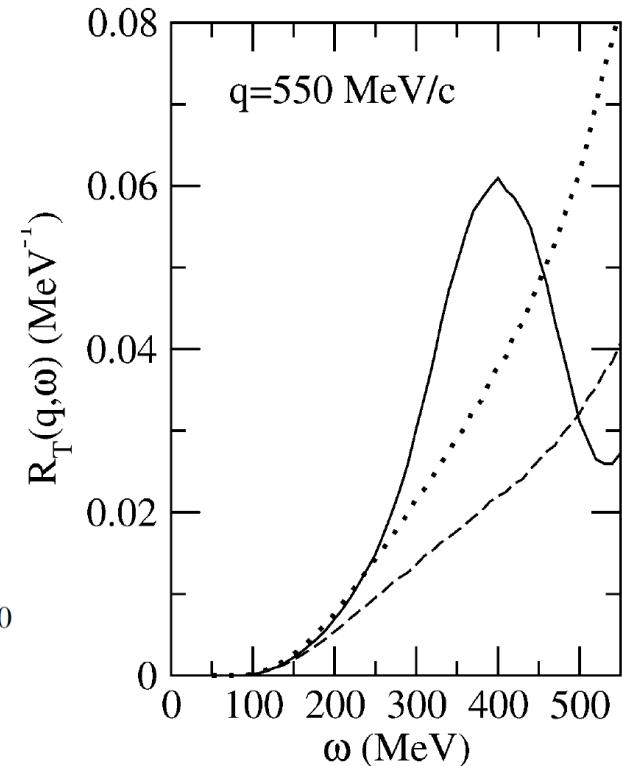
Our approach



Megias et al. Phys.Rev. D91, 073004 (2015)



De Pace et al. NPA741, 249 (2004)



Our evaluation is compatible with the one of Megias et al. which is a parameterization of the De Pace et al. results

Sources and References of 2p-2h

M. Martini, M. Ericson, G. Chanfray, J. Marteau

Alberico, Ericson, Molinari, Ann. Phys. 154, 356 (1984) (e,e') γ π
**Oset and Salcedo, Nucl. Phys. A 468, 631 (1987)* π γ
Shimizu, Faessler, Nucl. Phys. A 333, 495 (1980) π
Delorme, Ericson, Phys.Lett. B156 263 (1985)
Marteau, Eur.Phys.J. A5 183-190 (1999); PhD thesis
Marteau, Delorme, Ericson, NIM A 451 76 (2000)

}



pioneer works

J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas et al.

Gil, Nieves, Oset, Nucl. Phys. A 627, 543 (1997) (e,e') γ
**Oset and Salcedo, Nucl. Phys. A 468, 631 (1987)* π γ

J.E. Amaro, M.B. Barbaro, T.W. Donnelly G. Megias et al.

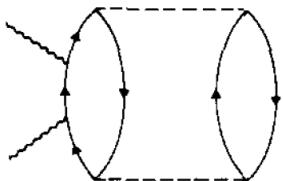
De Pace, Nardi, Alberico, Donnelly, Molinari, Nucl. Phys. A741, 249 (2004) (e,e') γ
Amaro, Maierová, Barbaro, Caballero, Donnelly, Phys. Rev. C 82 044601 (2010) (e,e')

A. Lovato, S. Gandolfi, J. Carlson, S. C. Pieper, R. Schiavilla

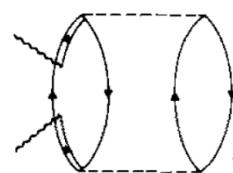
Lovato, Gandolfi, Butler, Carlson, Lusk, Pieper, Schiavilla, Phys. Rev. Lett. 111 092501 (2013) (e,e')
Shen, Marcucci, Carlson, Gandolfi, Schiavilla, Phys. Rev. C 86 035503 (2012) V- deuteron

Main difficulties in the 2p-2h sector

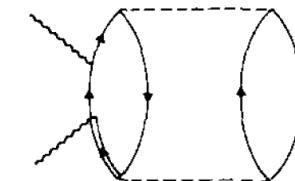
- Huge number of diagrams and terms



16 from NN correlations



49 from MEC



56 from interference

Alberico, Ericson, Molinari, Ann. Phys. 154, 356 (1984)

fully relativistic calculation (just of MEC !):

3000 direct terms

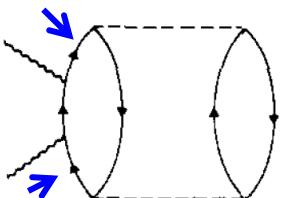
More than 100 000 exchange terms

De Pace, Nardi, Alberico, Donnelly, Molinari, Nucl. Phys. A741, 249 (2004)

- Divergences in NN correlations

$$(p_0 - E_p + i\epsilon)^{-2}$$

prescriptions:



- nucleon propagator only off the mass shell (*Alberico et al. Ann. Phys. 1984*)
- kinematical constraints + nucleon self energy in the medium (*Nieves et al PRC 83*)
- regularization parameter taking into account the finite size of the nucleus to be fitted to data (*Amaro et al. PRC 82 044601 2010*)

2p-2h phase space integral

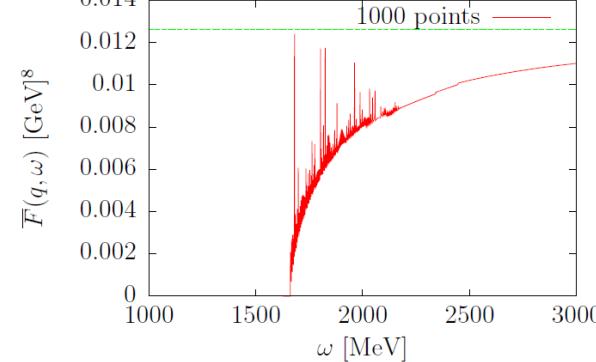
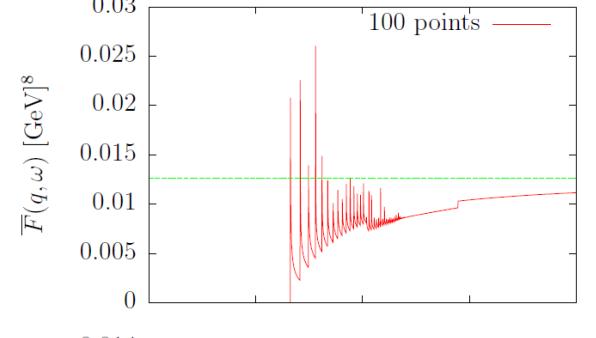
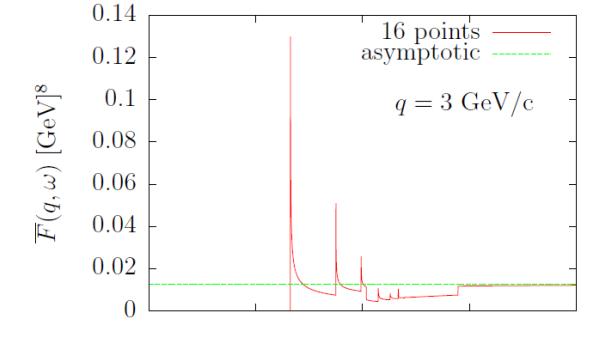
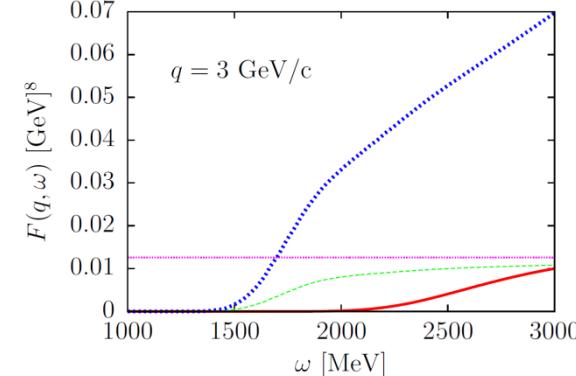
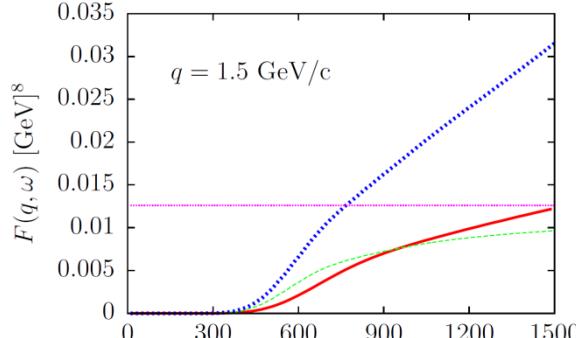
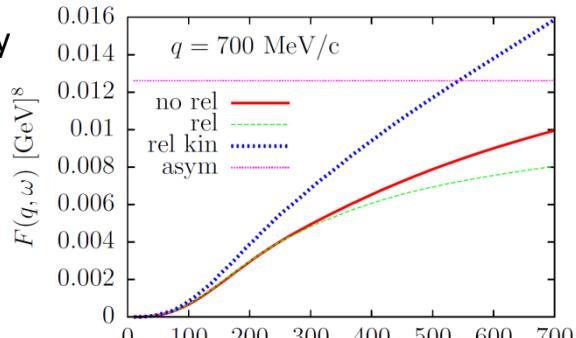
$$F(\omega, q) \equiv \int d^3 h_1 d^3 h_2 d^3 p'_1 \frac{m_N^4}{E_1 E_2 E'_1 E'_2} \Theta(p'_1, p'_2, h_1, h_2) \delta(E'_1 + E'_2 - E_1 - E_2 - \omega)$$

$$\bar{F}(\omega, q) = \left(\frac{4}{3} \pi k_F^3 \right)^2 \int d^3 p'_1 \delta(E'_1 + E'_2 - \omega - 2m_N) \Theta(p'_1, p'_2, 0, 0) \frac{m_N^2}{E'_1 E'_2}$$

Ruiz Simo, Albertus, Amaro, Barbaro, Caballero, Donnelly

Phys. Rev. D 90 033012 (2014)

Phys. Rev. D 90 053010 (2014)

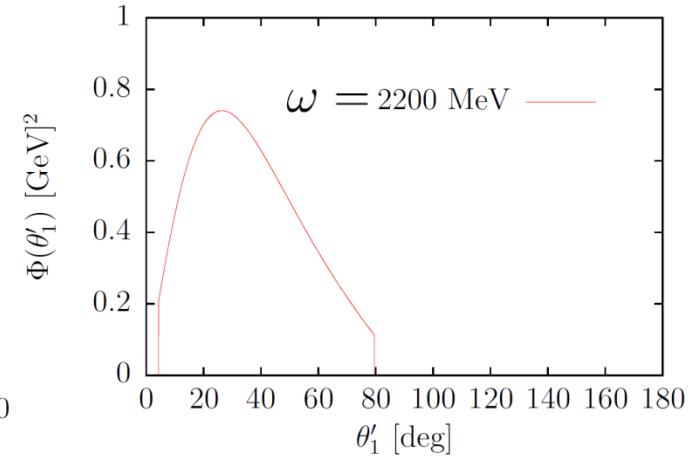
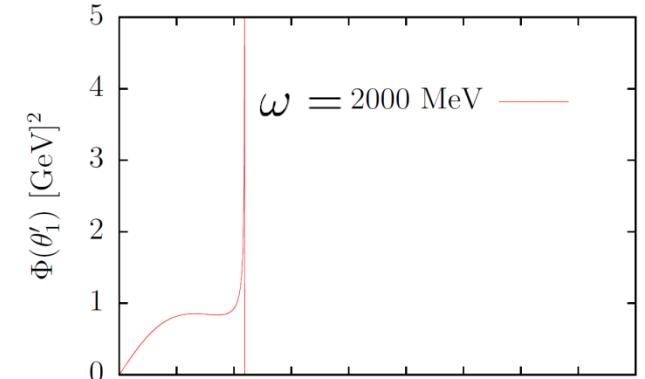
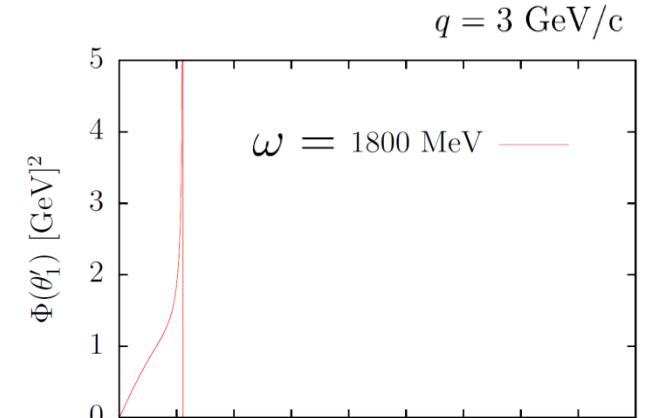
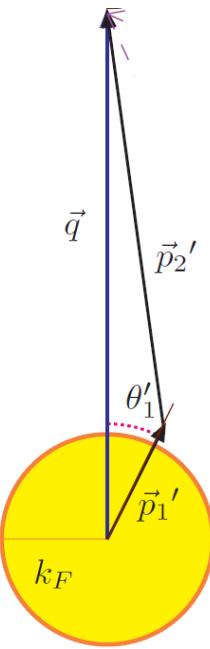


Angular distribution of ejected nucleons

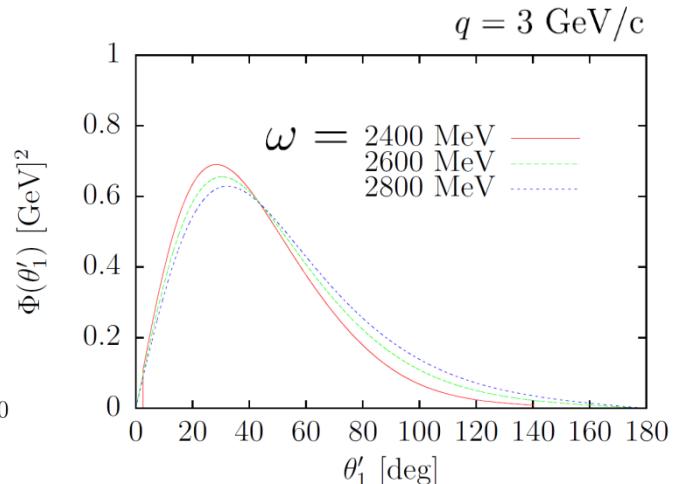
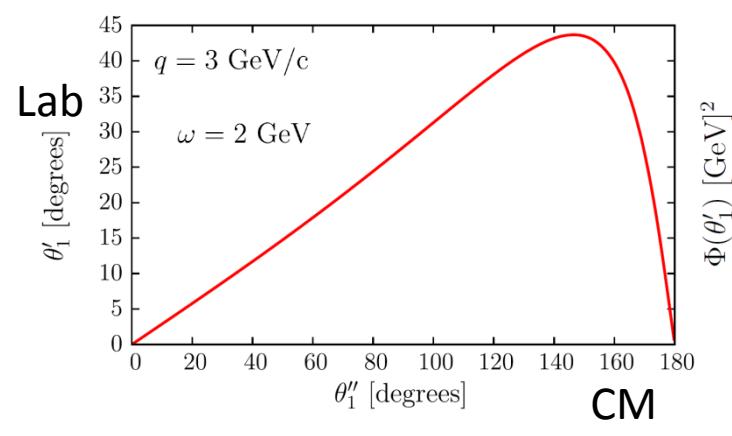
$$\bar{F}(\omega, q) = \left(\frac{4}{3} \pi k_F^3 \right)^2 2\pi \int_0^\pi d\theta'_1 \Phi(\theta'_1)$$

$$\Phi(\theta'_1) = \sin \theta'_1 \int p'_1{}^2 dp'_1 \delta(E_1 + E_2 + \omega - E'_1 - E'_2)$$

$$\begin{aligned} & \times \Theta(p'_1, p'_2, h_1, h_2) \frac{m_N^4}{E_1 E_2 E'_1 E'_2} \\ &= \sum_{\alpha=\pm} \frac{m_N^4 \sin \theta'_1 p'_1{}^2 \Theta(p'_1, p'_2, h_1, h_2)}{E_1 E_2 E'_1 E'_2 \left| \frac{p'_1}{E'_1} - \frac{\mathbf{p}'_2 \cdot \hat{\mathbf{p}}'_1}{E'_2} \right|} \Bigg|_{p'_1=p'_1^{(\alpha)}} \end{aligned}$$



Ruiz Simo, Albertus, Amaro, Barbaro, Caballero, Donnelly
 Phys. Rev. D 90 033012 (2014)
 Phys. Rev. D 90 053010 (2014)



Single nucleon weak CC current

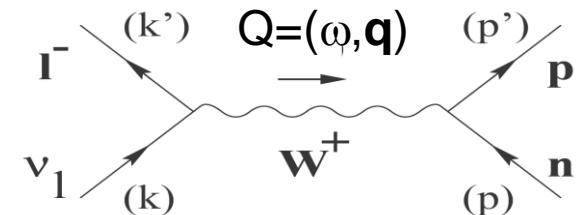
$$j^\mu = j_V^\mu - j_A^\mu$$

$$j_V^\mu(\mathbf{p}', \mathbf{p}) = \bar{u}(\mathbf{p}') \left[2F_1^V \gamma^\mu + i \frac{F_2^V}{m_N} \sigma^{\mu\nu} Q_\nu \right] u(\mathbf{p})$$

$$j_A^\mu(\mathbf{p}', \mathbf{p}) = \bar{u}(\mathbf{p}') \left[G_A \gamma^\mu + G_P \frac{Q^\mu}{2m_N} \right] \gamma^5 u(\mathbf{p})$$

$$\mathcal{L}_W = \frac{G_F}{\sqrt{2}} \cos \theta_C l_\mu J^\mu$$

$$\langle k', s' | l_\mu | k, s \rangle = e^{-iqx} \bar{u}(k', s') [\gamma_\mu (1 - \gamma_5)] u(k, s)$$



Some two-body currents

Electromagnetic

- Seagull or contact:

$$j_s^\mu(\mathbf{p}'_1, \mathbf{p}'_2, \mathbf{p}_1, \mathbf{p}_2) = \frac{f^2}{m_\pi^2} i\epsilon_{3ab} \bar{u}(\mathbf{p}'_1) \tau_a \gamma_5 K_1 u(\mathbf{p}_1) \frac{F_1^V}{K_1^2 - m_\pi^2} \bar{u}(\mathbf{p}'_2) \tau_b \gamma_5 \gamma^\mu u(\mathbf{p}_2) + (1 \leftrightarrow 2).$$

- Pion-in-flight:

$$j_p^\mu(\mathbf{p}'_1, \mathbf{p}'_2, \mathbf{p}_1, \mathbf{p}_2) = \frac{f^2}{m_\pi^2} i\epsilon_{3ab} \frac{F_\pi(K_1 - K_2)^\mu}{(K_1^2 - m_\pi^2)(K_2^2 - m_\pi^2)} \bar{u}(\mathbf{p}'_1) \tau_a \gamma_5 K_1 u(\mathbf{p}_1) \bar{u}(\mathbf{p}'_2) \tau_b \gamma_5 K_2 u(\mathbf{p}_2).$$

- Correlation:

$$\begin{aligned} j_{\text{cor}}^\mu(\mathbf{p}'_1, \mathbf{p}'_2, \mathbf{p}_1, \mathbf{p}_2) = & \frac{f^2}{m_\pi^2} \bar{u}(\mathbf{p}'_1) \tau_a \gamma_5 K_1 u(\mathbf{p}_1) \frac{1}{K_1^2 - m_\pi^2} \bar{u}(\mathbf{p}'_2) [\tau_a \gamma_5 K_1 S_F(P_2 + Q) \Gamma^\mu(Q) \\ & + \Gamma^\mu(Q) S_F(P'_2 - Q) \tau_a \gamma_5 K_1] u(\mathbf{p}_2) + (1 \leftrightarrow 2). \end{aligned}$$

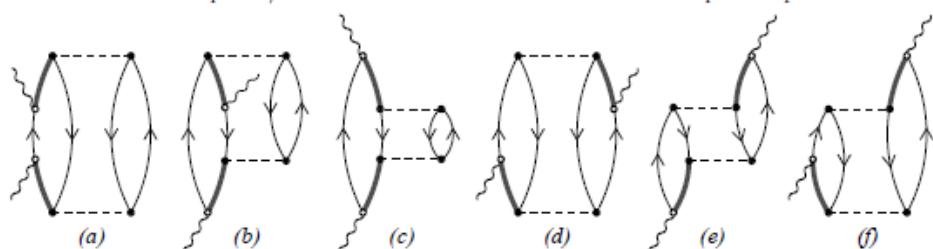
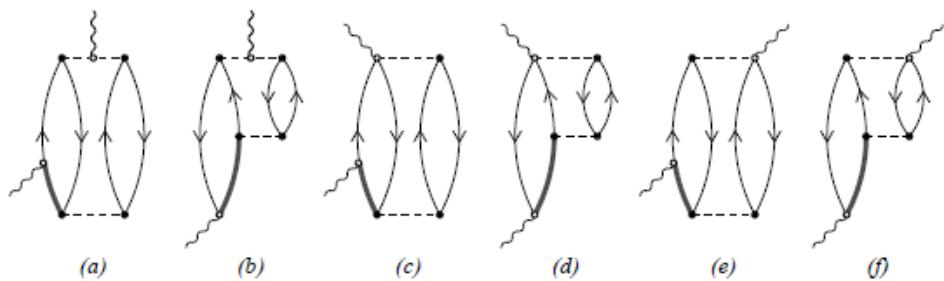
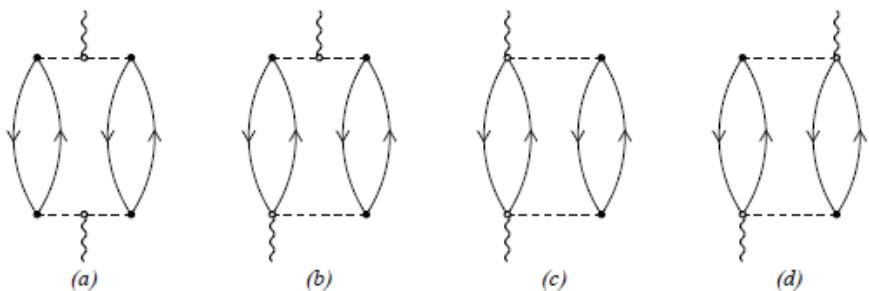
Weak

- CC Seagull

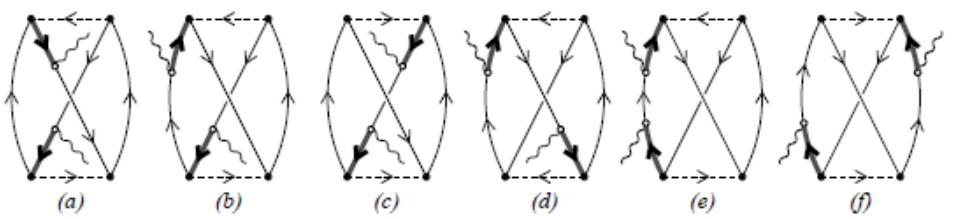
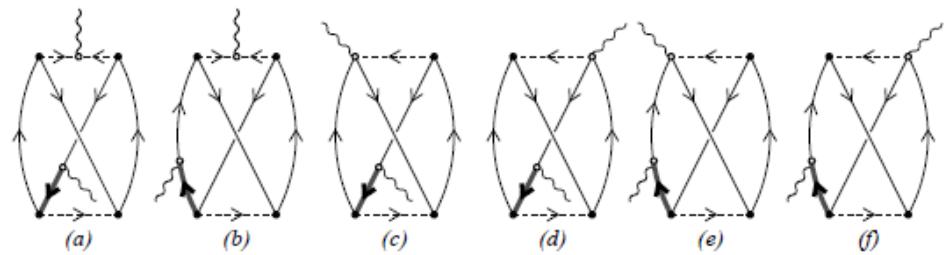
$$\begin{aligned} j_s^\mu(\mathbf{p}'_1, \mathbf{p}'_2, \mathbf{h}_1, \mathbf{h}_2) = & \tau_0 \otimes \tau_{+1} - \tau_{+1} \otimes \tau_0 \frac{f}{m_\pi} \frac{1}{\sqrt{2} f_\pi} \bar{u}(\mathbf{p}'_1) \gamma_5 K_1 u(\mathbf{h}_1) \frac{\bar{u}(\mathbf{p}'_2) [g_A F_1^V(Q^2) \gamma_5 \gamma^\mu + F_\rho(K_2^2) \gamma^\mu]}{K_1^2 - m_\pi^2} u(\mathbf{h}_2) \\ & - (1 \leftrightarrow 2) \end{aligned}$$

MEC

Direct



Exchange



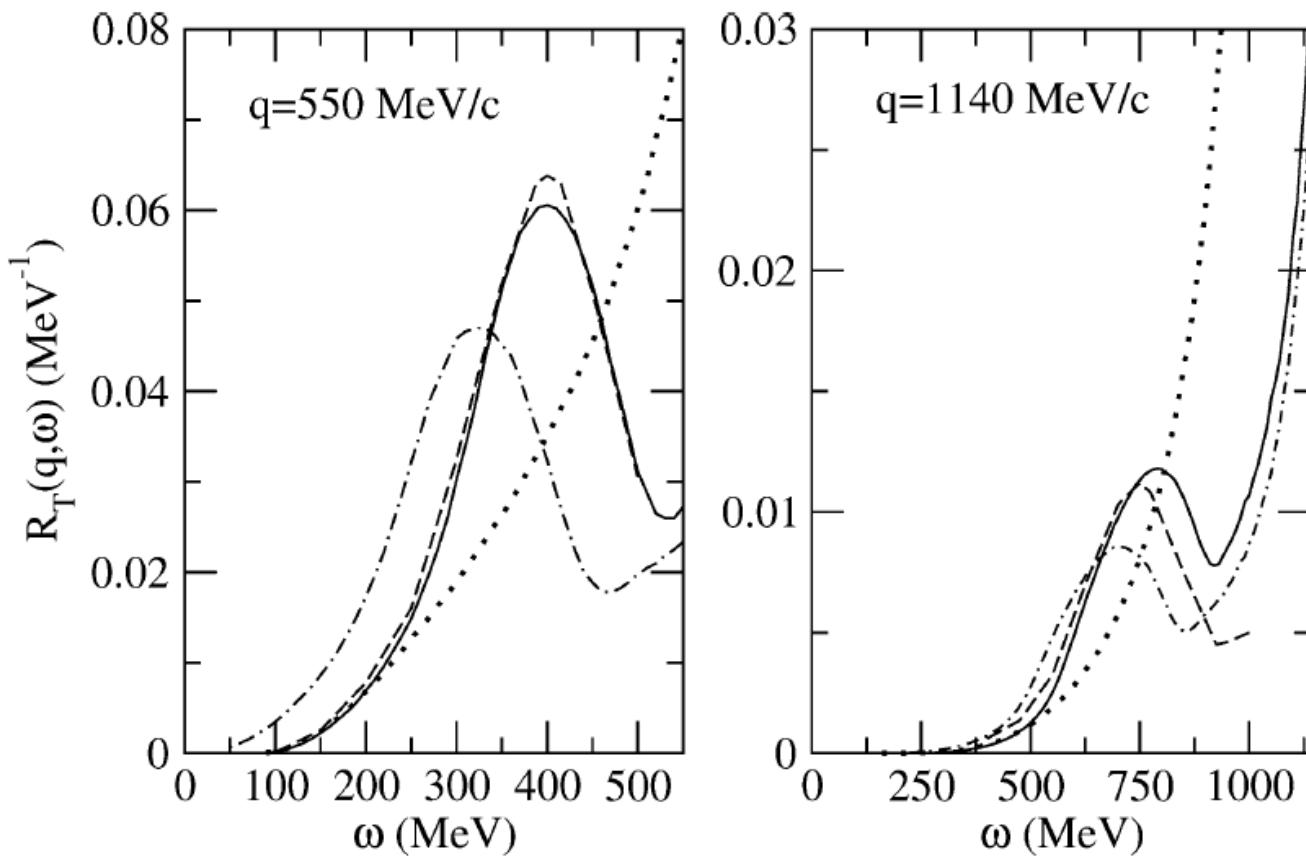


Fig. 8. The relativistic transverse response function $R_T(q, \omega)$ at $q = 550 \text{ MeV}/c$ and $q = 1140 \text{ MeV}/c$ calculated with $\bar{\epsilon}_2 = 70 \text{ MeV}$ (solid) and with $\bar{\epsilon}_2 = 0$ (dot-dashed). Only the direct contribution is shown. The non-relativistic results are also displayed in order to shed light on the role of relativity in the response (dotted). For the sake of comparison the relativistic results obtained in DBT are displayed (dashed). In all instances $k_F = 1.3 \text{ fm}^{-1}$.

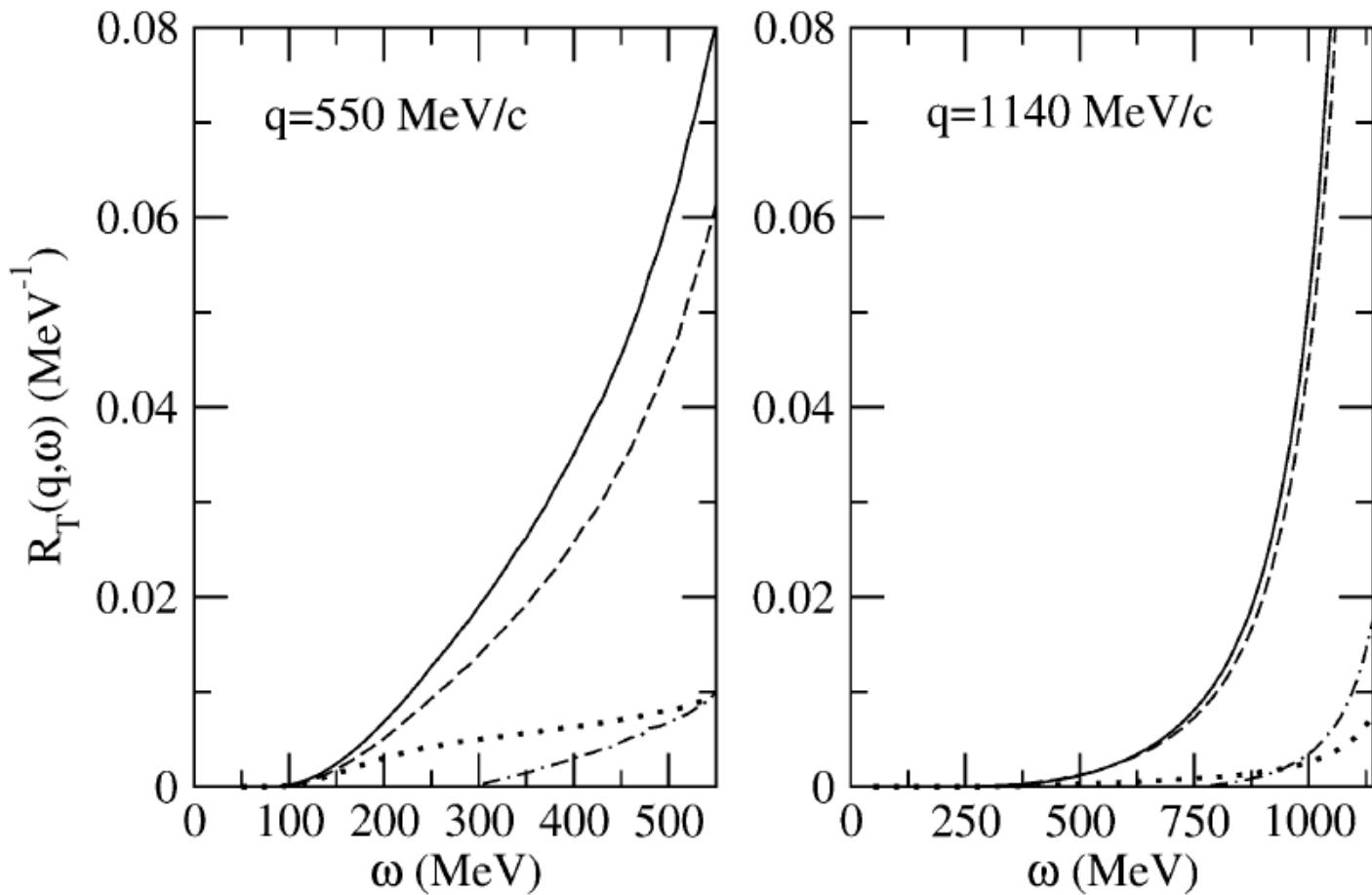


Fig. 9. Separate contributions to the transverse response function $R_T(q, \omega)$ in the non-relativistic limit at $q = 550 \text{ MeV}/c$ and $q = 1140 \text{ MeV}/c$: pionic (dotted), pionic- Δ interference (dash-dotted), Δ (dashed) and total (solid); $k_F = 1.3 \text{ fm}^{-1}$. The exchange contribution is disregarded here.

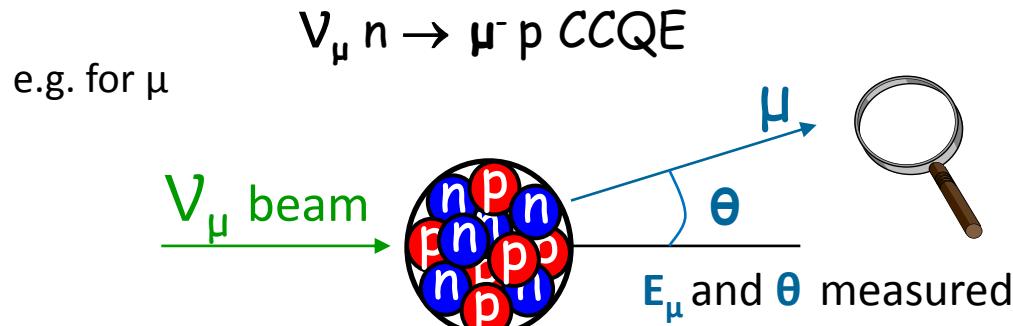
Neutrino energy reconstruction problems and neutrino oscillations

Towards the neutrino oscillation physics

Neutrino oscillation experiments require the determination of the neutrino energy which enters the expression of the oscillation probability.

The neutrino energy is unknown. We know only broad fluxes.

The determination of the neutrino energy is done through
Charged Current QuasiElastic events.



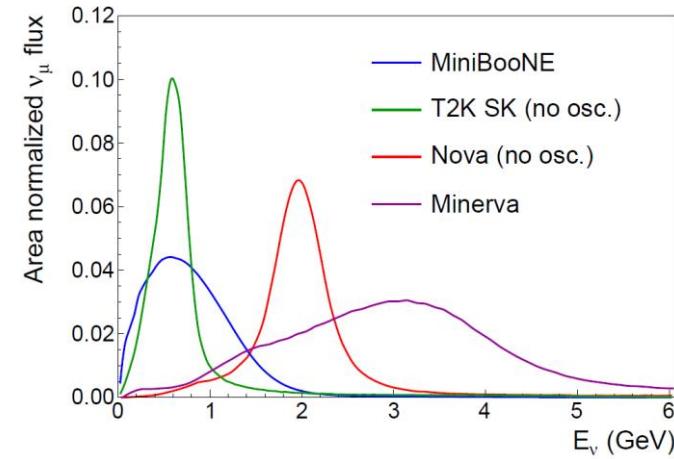
Reconstructed neutrino energy

$$\overline{E}_\nu = \frac{E_\mu - m_\mu^2/(2M)}{1 - (E_\mu - P_\mu \cos \theta)/M}$$

via two-body
kinematics

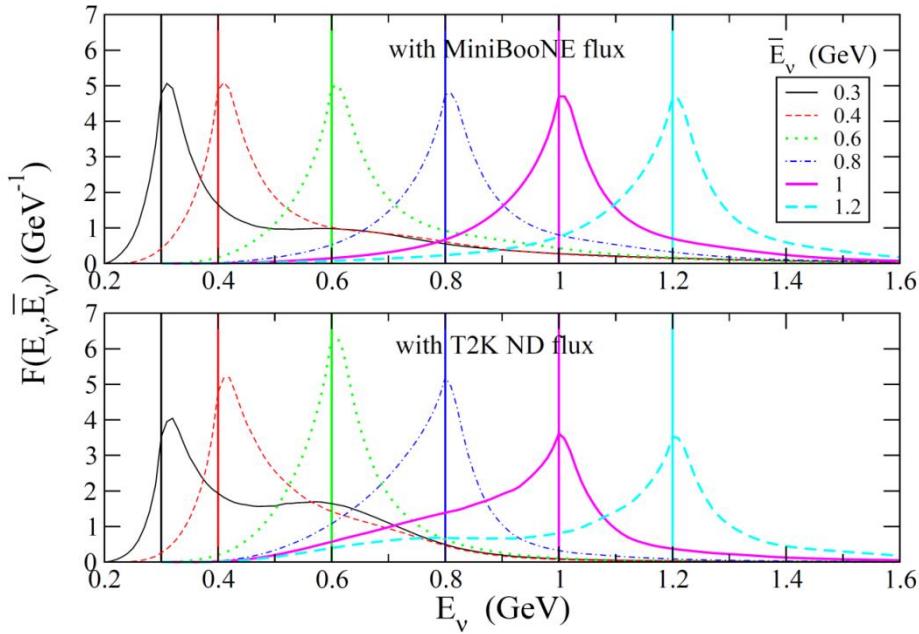
$\overline{E}_\nu = E_\nu$ is exact only for CCQE with free nucleon

reconstructed neutrino energy \overline{E}_ν $\xleftrightarrow{?} E_\nu$ true neutrino energy



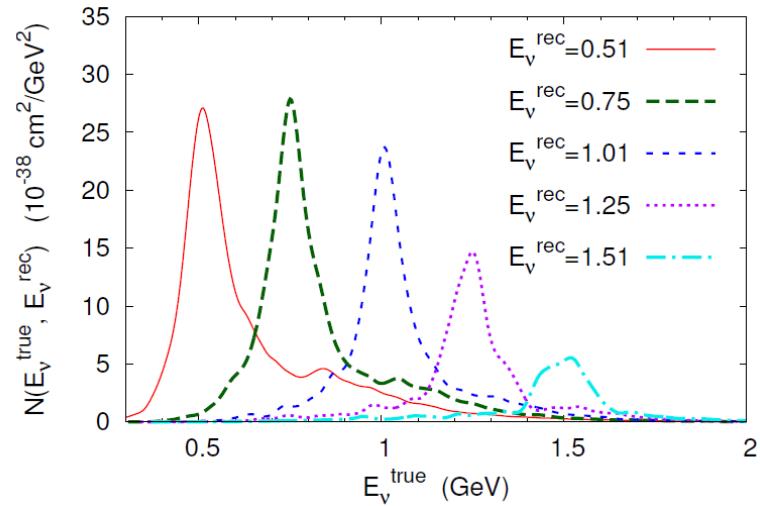
Distributions in terms of true E_ν for fixed values of reconstructed \bar{E}_ν

Martini, Ericson, Chanfray, PRD 85 093012 (2012)

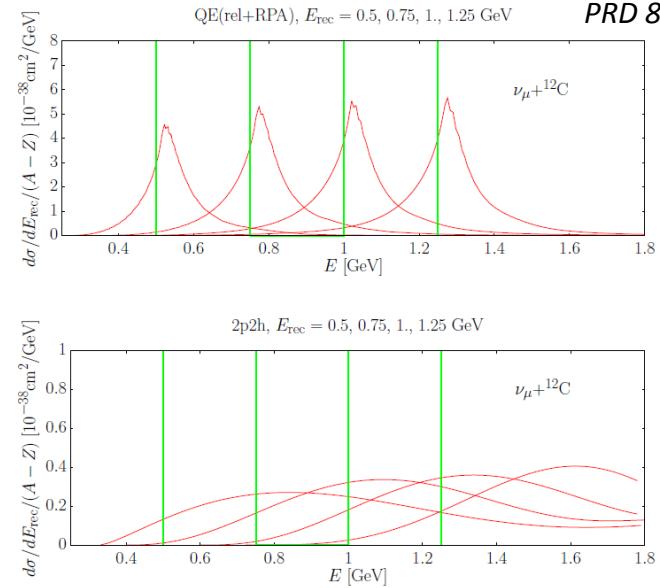


- The distributions are not symmetrical around \bar{E}_ν .
- The asymmetry favors higher energies at low \bar{E}_ν and smaller energies for large \bar{E}_ν .
- Crucial role of neutrino flux.

O. Lalakulich, U. Mosel, K. Gallmeister PRC 86 054606 (2012)



J. Nieves, F. Sanchez, I. Ruiz Simo, M.J. Vicente Vacas
QE(rel+RPA), $E_{\text{rec}} = 0.5, 0.75, 1., 1.25 \text{ GeV}$
PRD 85 113008 (2012)



From true neutrino energy to reconstructed neutrino energy

Probability energy distribution (E_ν, \bar{E}_ν)

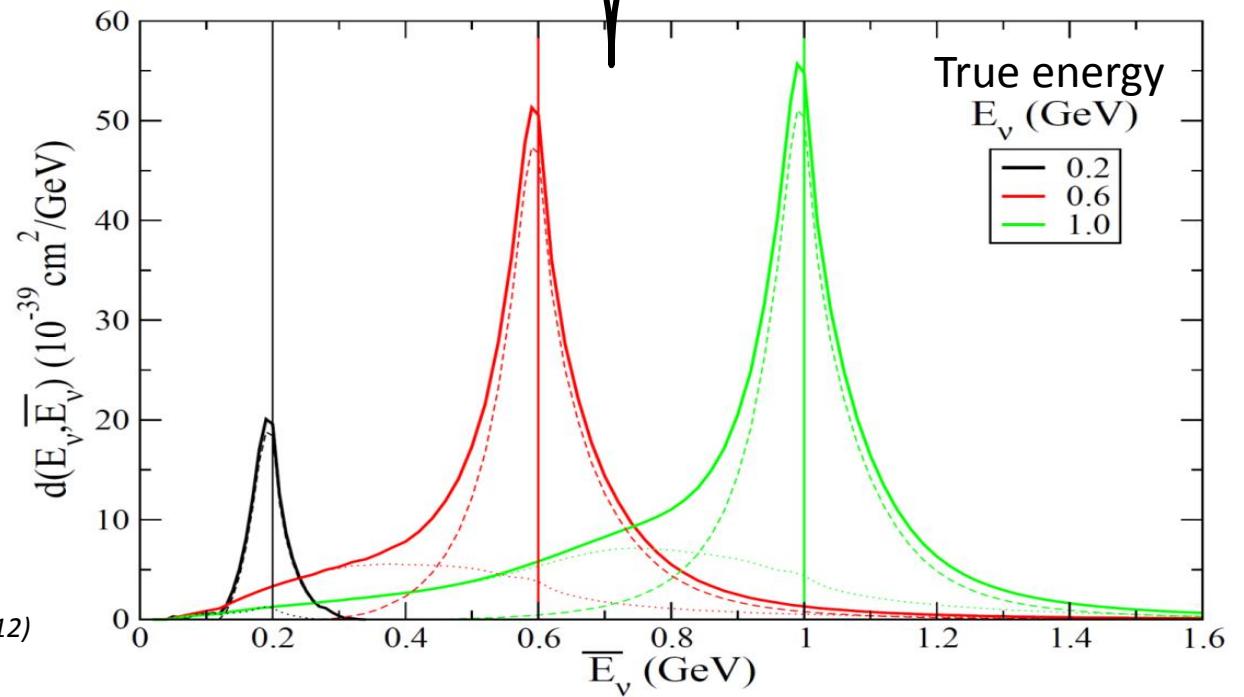
$$D_{rec}(\bar{E}_\nu) = \int dE_\nu \Phi(E_\nu) \left[\int_{E_l^{min}}^{E_l^{max}} dE_l \frac{ME_l - m_l^2/2}{\bar{E}_\nu^2 P_l} \left[\frac{d^2\sigma}{d\omega d\cos\theta} \right]_{\omega=E_\nu-E_l, \cos\theta=\cos\theta(E_l, \bar{E}_\nu)} \right]$$

The quantity $D_{rec}(\bar{E}_\nu)$ corresponds to the product $\sigma(E_\nu)\Phi(E_\nu)$ but in terms of reconstructed neutrino energy

M. Martini, M. Ericson, G. Chanfray

- Phys. Rev. D 85 093012 (2012)

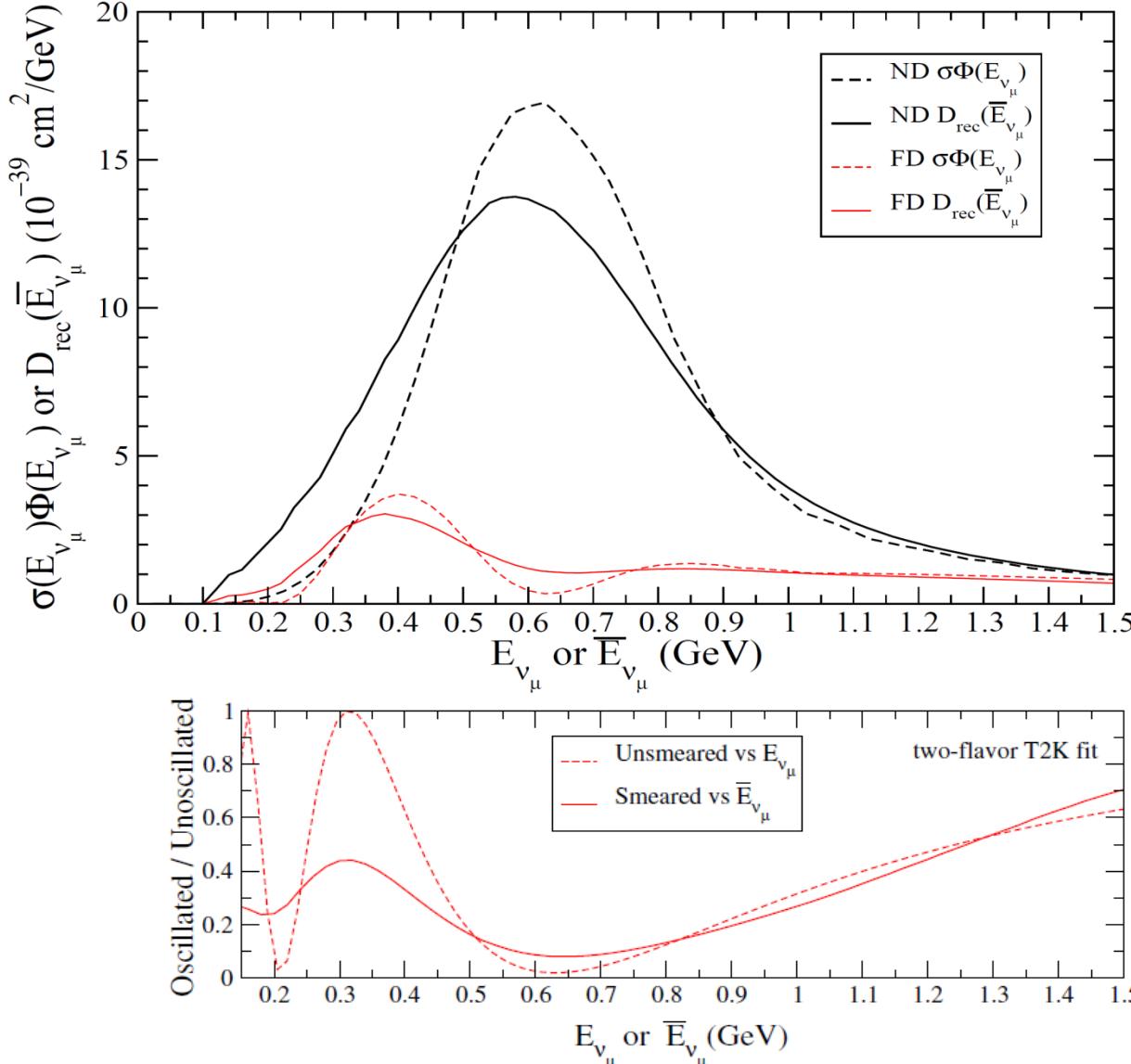
- Phys. Rev. D 87 013009 (2013)



- Distributions not symmetrical around E_ν
- Crucial role of np-nh: low energy tail

ν_μ disappearance T2K

PRD85 (2012); PRL 111 (2013)



After reconstruction correction:

- Near Detector:
clear low energy enhancement
- Far Detector:
low energy tail and
the middle hole is largely filled
Effects largely due to np-nh

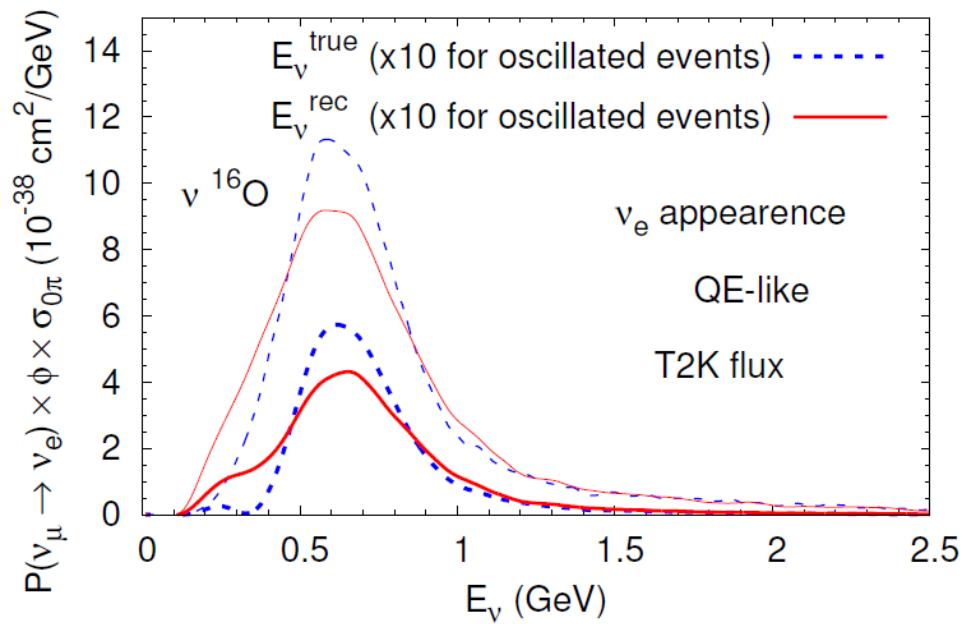
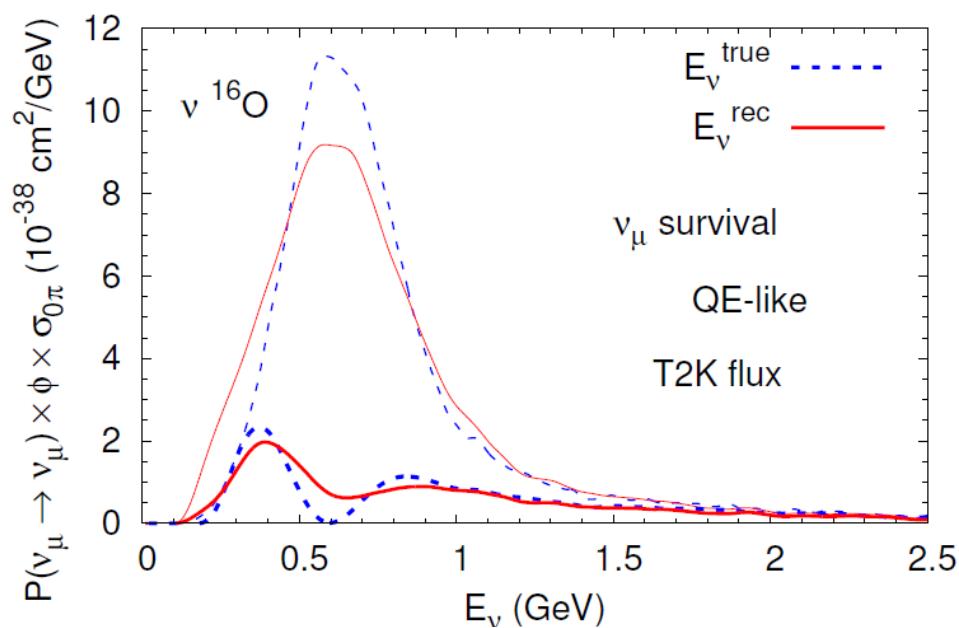
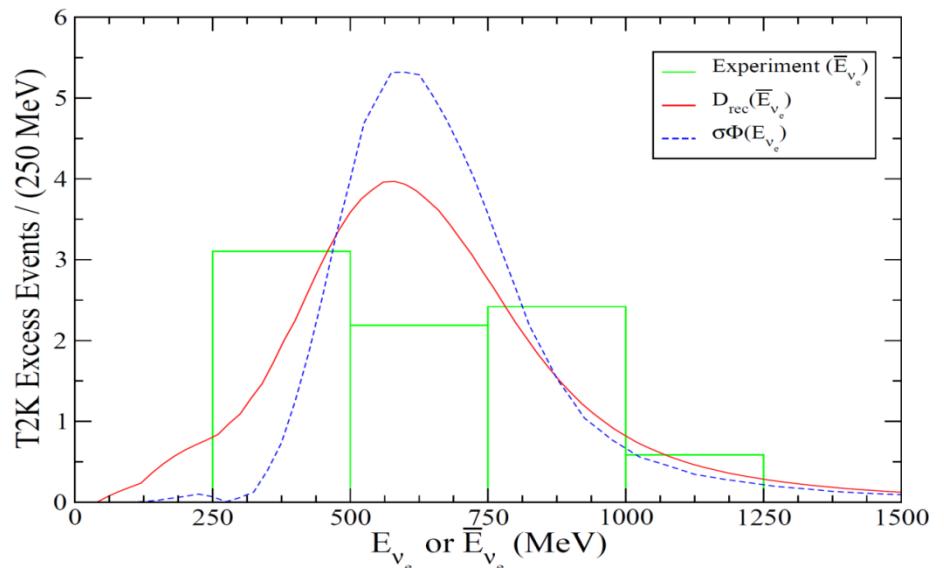
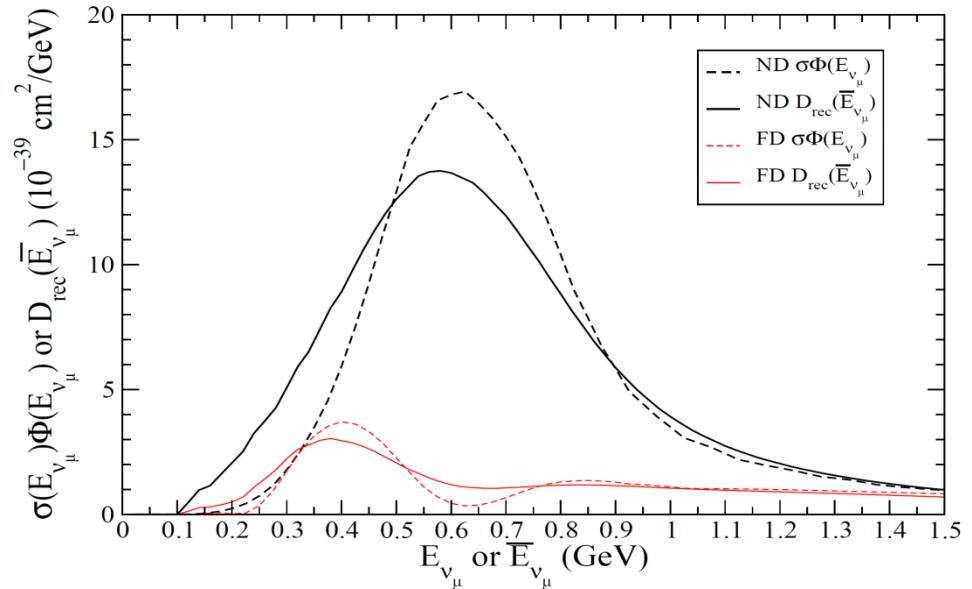
Recent T2K experimental analysis :

PhysRevD.91.072010 (2015)

“For the present exposure, the effect can be ignored, but future analyses will need to incorporate multi-nucleon effects in their model of neutrino-nucleus interactions.”

M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)

Similar results in: O. Lalakulich, U. Mosel, K. Gallmeister, PRC 86 054606 (2012)



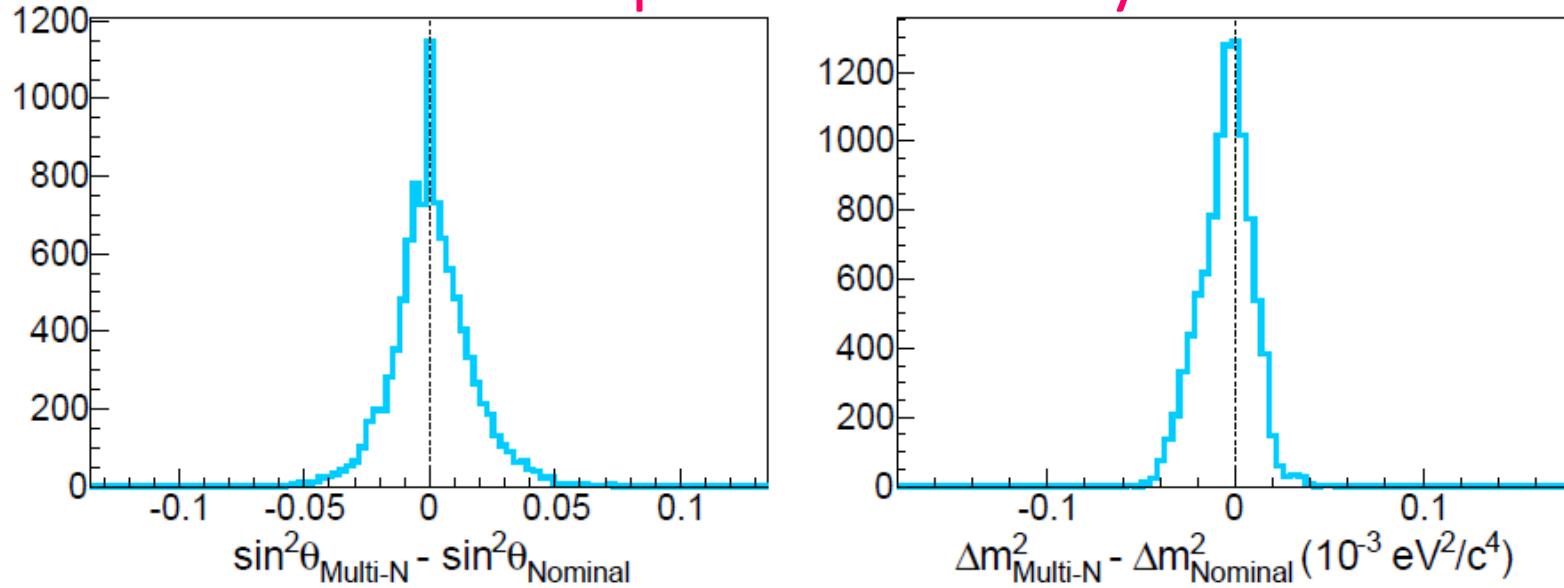
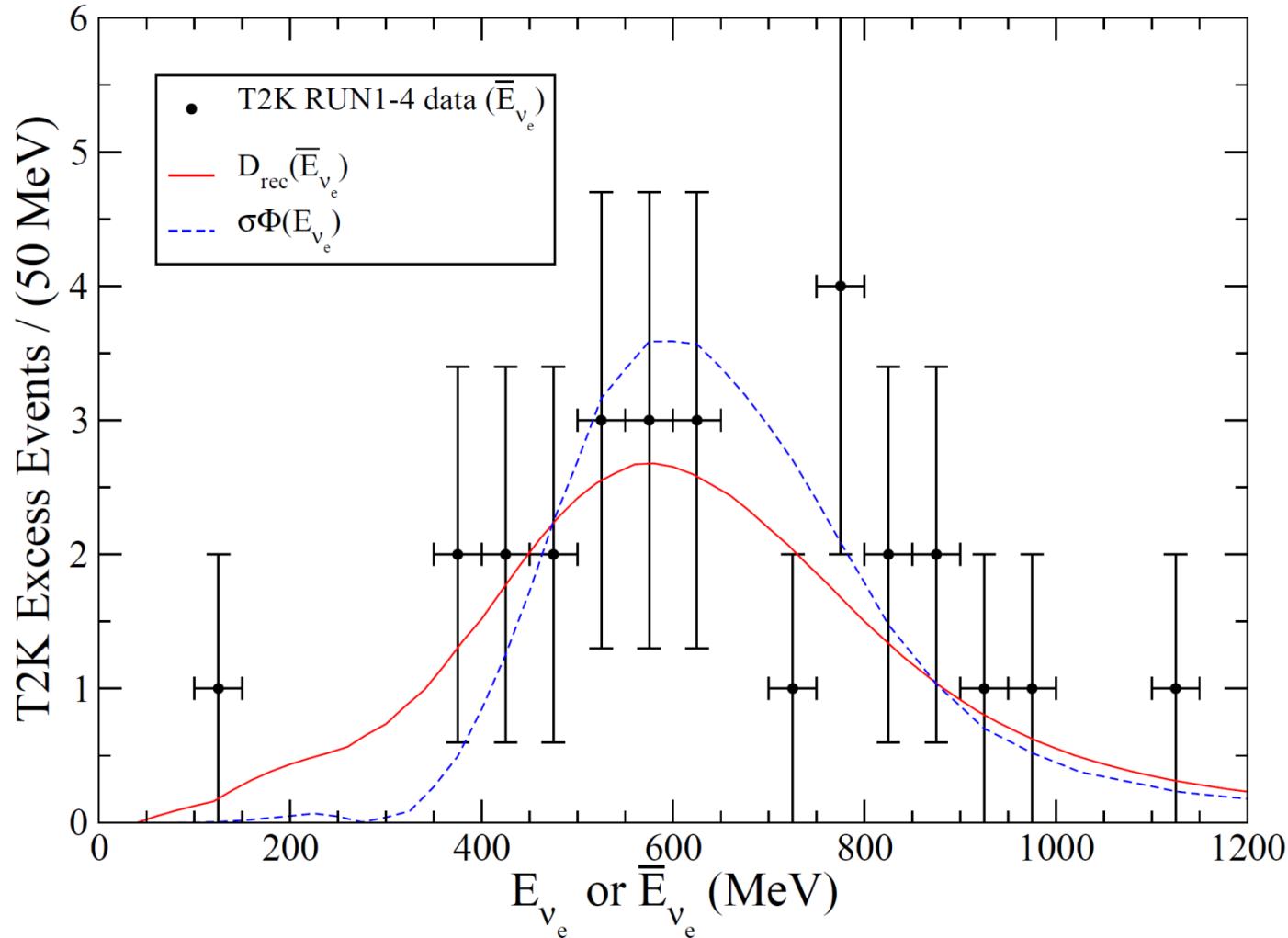


FIG. 30: Difference in the point estimates of $\sin^2\theta_{23}$ (left) and $|\Delta m^2|$ (right) between pairs of toy MC datasets with and without including multi-nucleon effects.

The overall bias for both is negligible, compared to the precision obtained for the parameters. However, the additional variation in $\sin^2\theta_{23}$ is about 3%, comparable to the size of other systematic uncertainties. The bias was evaluated at $\sin^2\theta_{23} = 0.45$ to avoid the physical boundary at maximal disappearance which could reduce the size of the apparent bias. For the present exposure, the effect can be ignored, but future analyses will need to incorporate multi-nucleon effects in their model of neutrino-nucleus interactions.

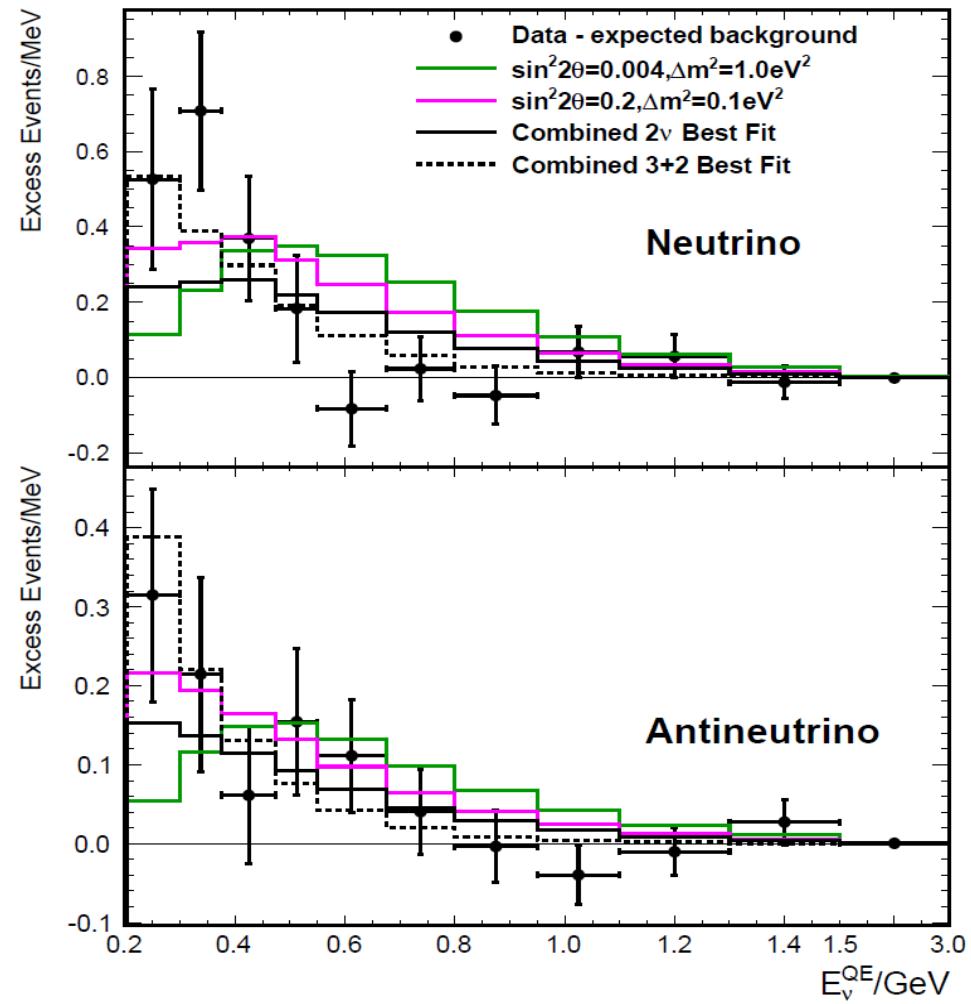
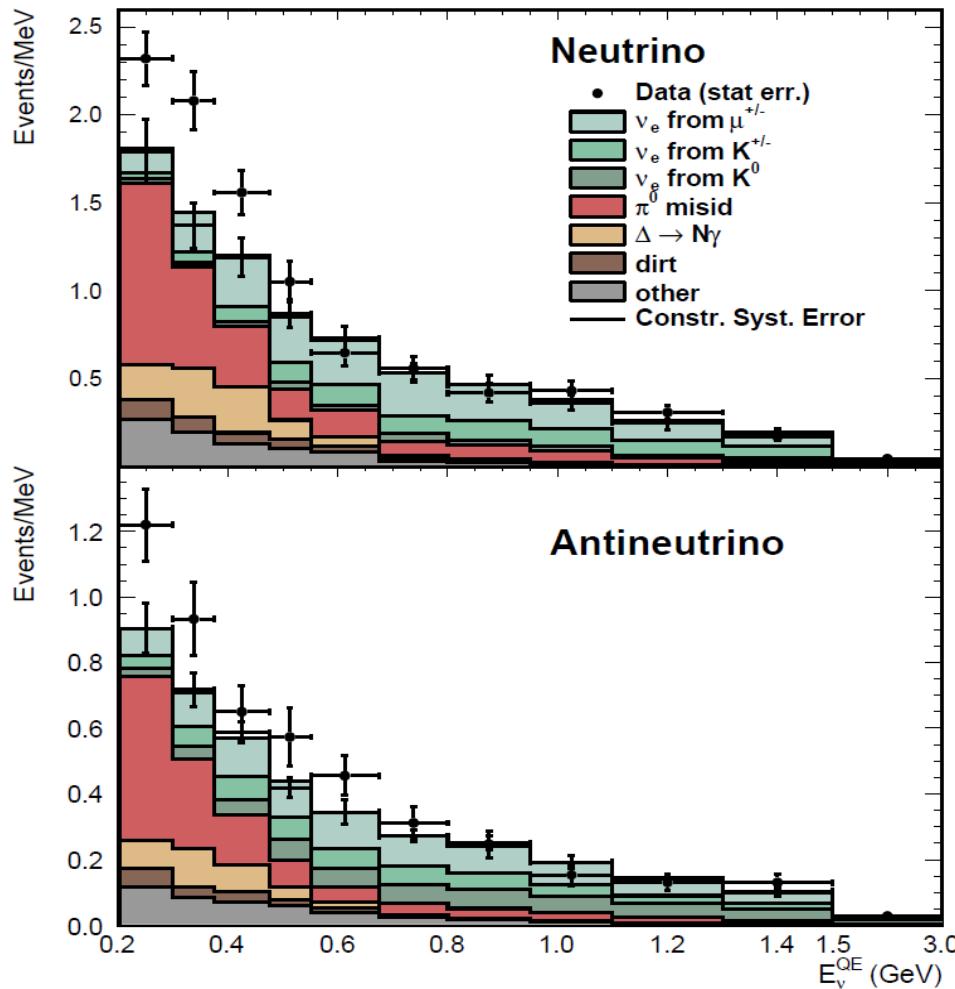
2013: 28 events



The reconstruction correction tends to make events leak outside the high flux region, especially towards the low energy side

$\nu_\mu \rightarrow \nu_e$ MiniBooNE

PRL 98 (2007), PRL 102 (2009), PRL 105 (2010), PRL 110 (2013)

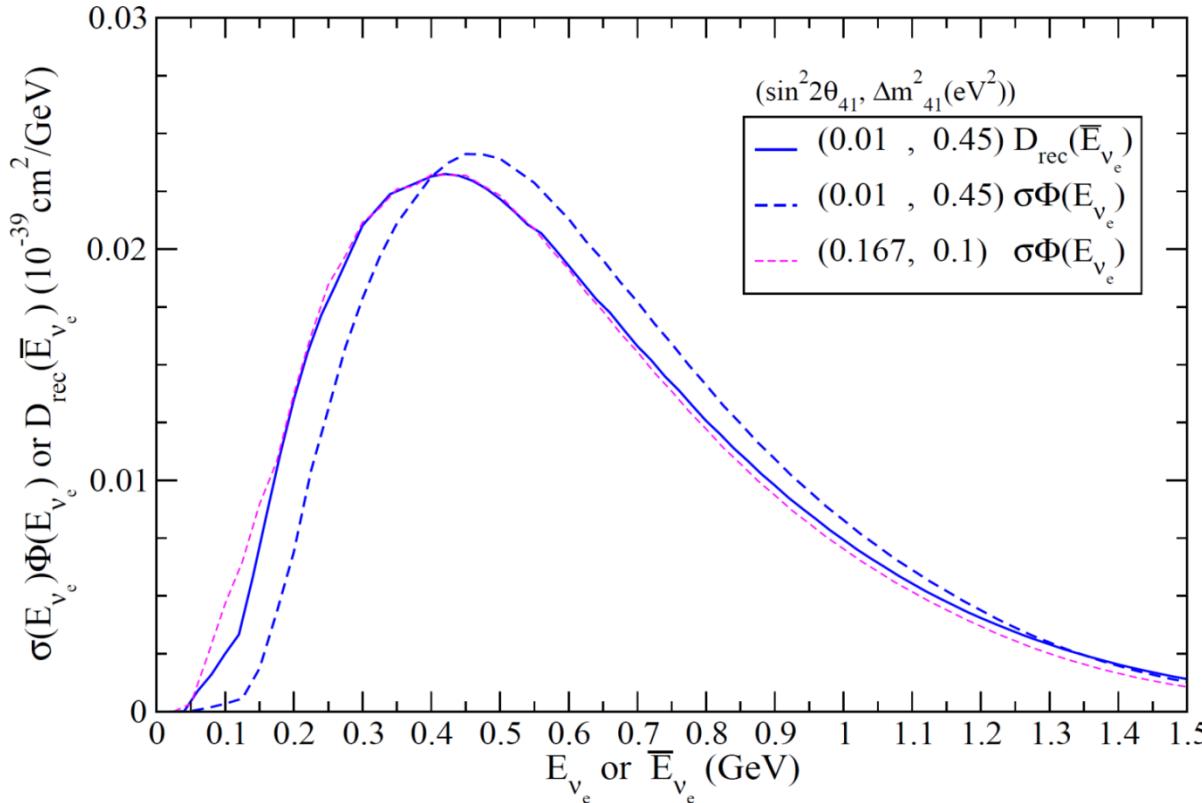


MiniBooNE Anomaly: Excess of events at low energies

Sterile neutrino??

Taking into account the energy reconstruction correction

M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)



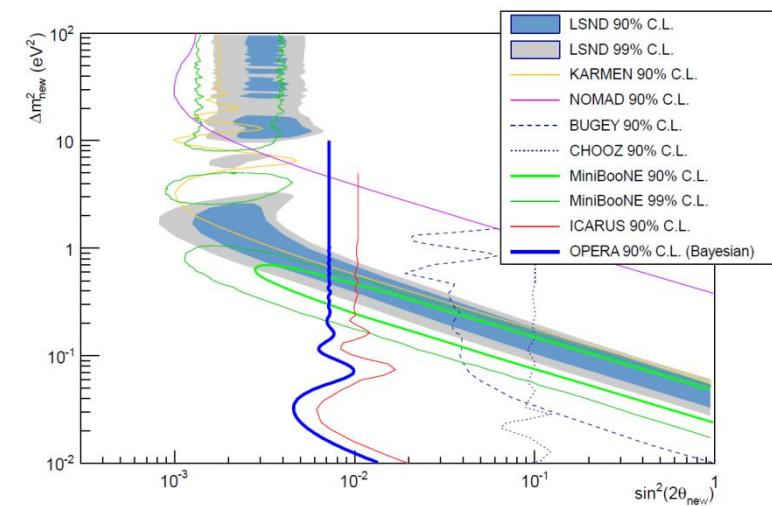
A large mass value allows the same quality of fit of data than is obtained in the unsmeared case with a much smaller mass.

The energy reconstruction leads to an increase of the oscillation mass parameters



Gain for the compatibility with the existing constraints

OPERA, JHEP 1307 (2013) 004,
Addendum-*ibid.* 1307 (2013) 085



$\nu_\mu \rightarrow \nu_e$ MiniBooNE

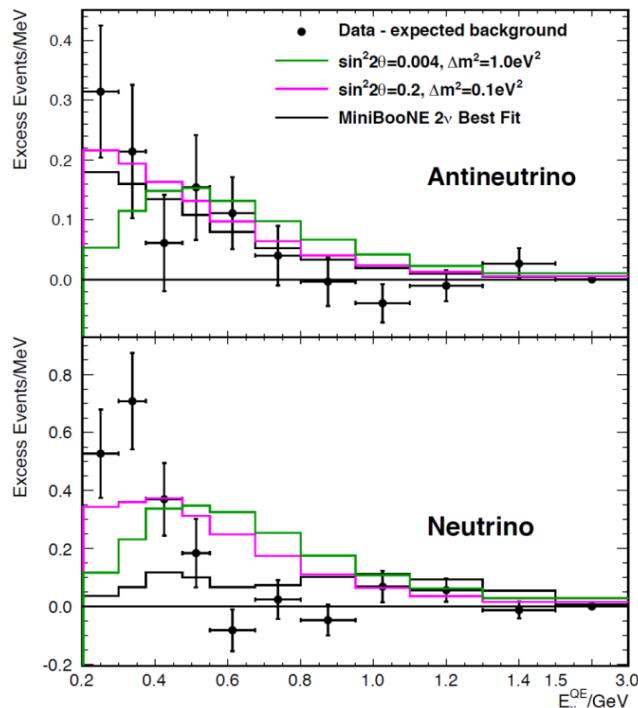


TABLE II: χ^2 values from oscillation fits to the antineutrino-mode data for different prediction models. The best fit ($\Delta m^2, \sin^2 2\theta$) values are $(0.043 \text{ eV}^2, 0.88)$, $(0.059 \text{ eV}^2, 0.64)$, and $(0.177 \text{ eV}^2, 0.070)$ for the nominal, Martini, and disappearance models, respectively. The test point χ^2 values in the third column are for $\Delta m^2 = 0.5 \text{ eV}^2$ and $\sin^2 2\theta = 0.01$. The effective dof values are approximately 6.9 for best fits and 8.9 for the test points.

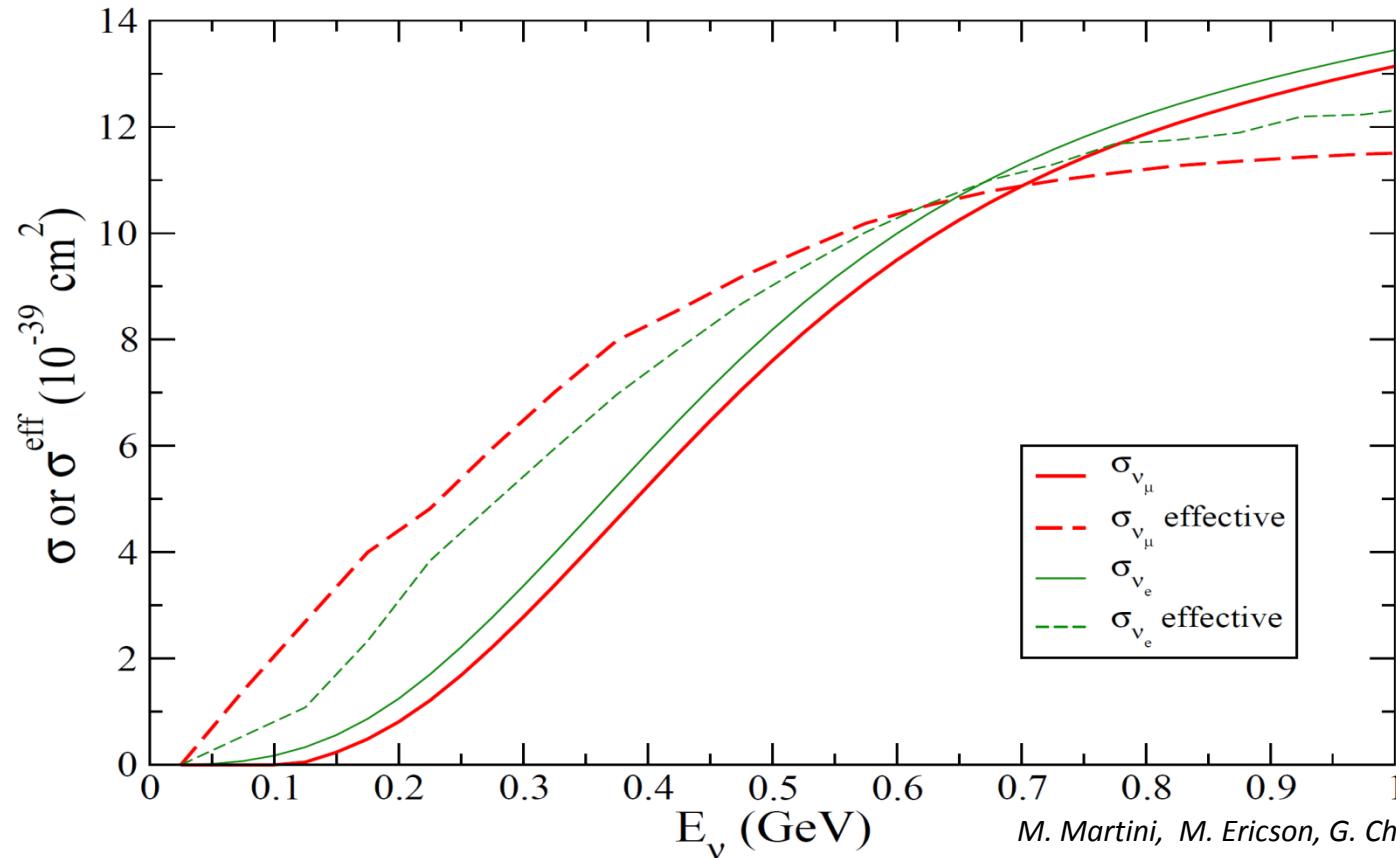
Prediction Model	χ^2 values	
	Best Fit	Test Pt.
Nominal $\bar{\nu}$ -mode Result	5.0	6.2
Martini <i>et al.</i> [25] Model	5.5	6.5
Model With Disapp. (see text)	5.4	6.7

Phys.Rev.Lett. 110 (2013) 161801

Real and effective cross sections for ν_μ and ν_e

Let's define the effective cross section through $D_{\text{rec}}(\bar{E}_\nu) = \sigma_\nu^{\text{eff}}(\bar{E}_\nu)\Phi(\bar{E}_\nu)$

Let's then ignore the difference between the true and reconstructed neutrino energies

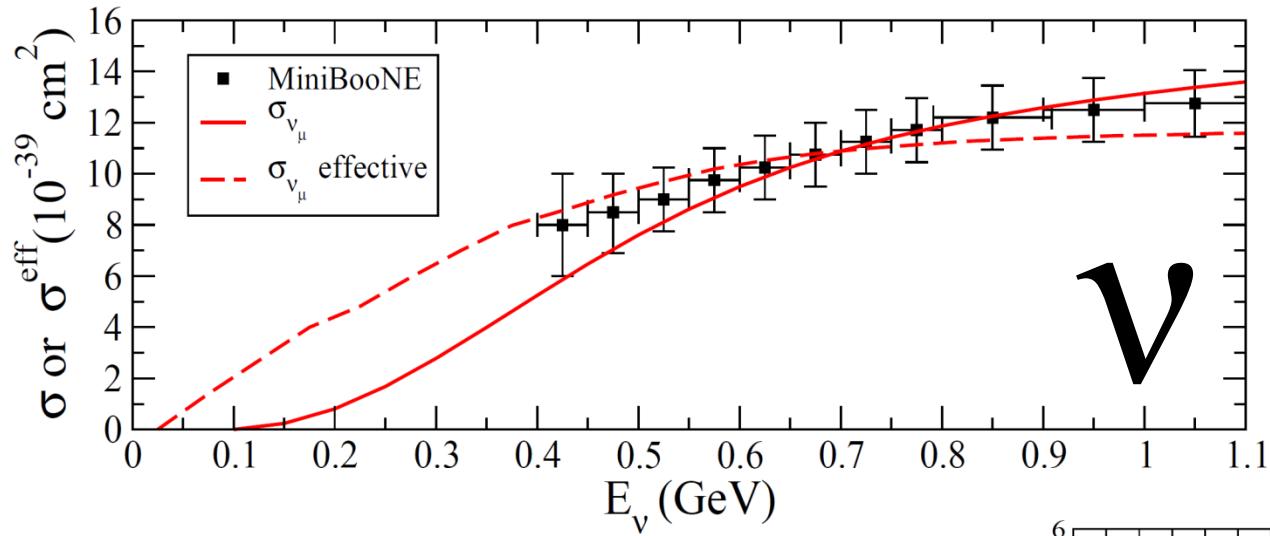


M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)

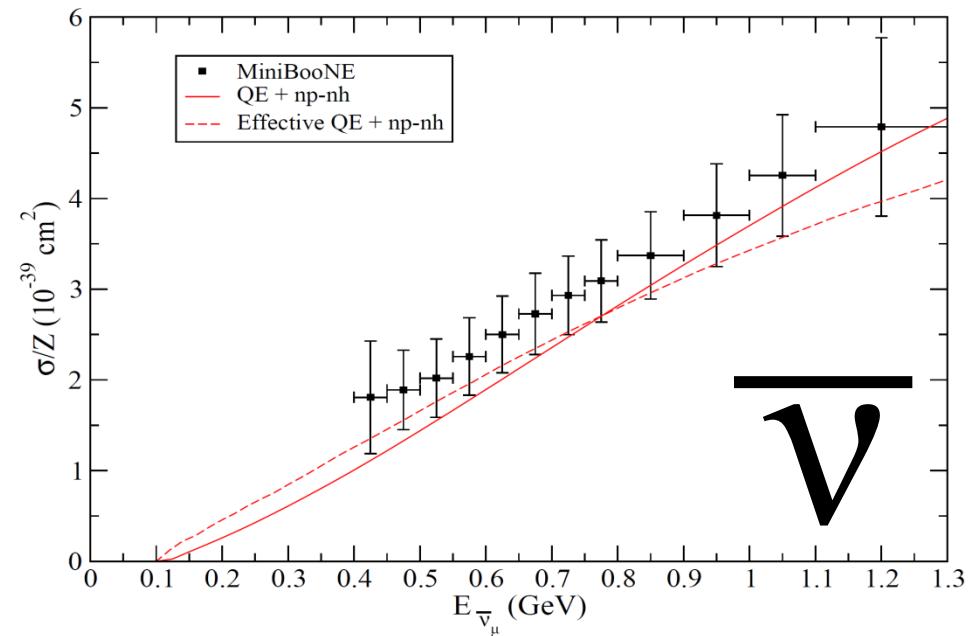
The effective cross section is not universal but
it depends on the particular beam energy distribution

(here we used ν_μ and ν_e MiniBooNE fluxes)

Real and effective cross sections for μ



V



V